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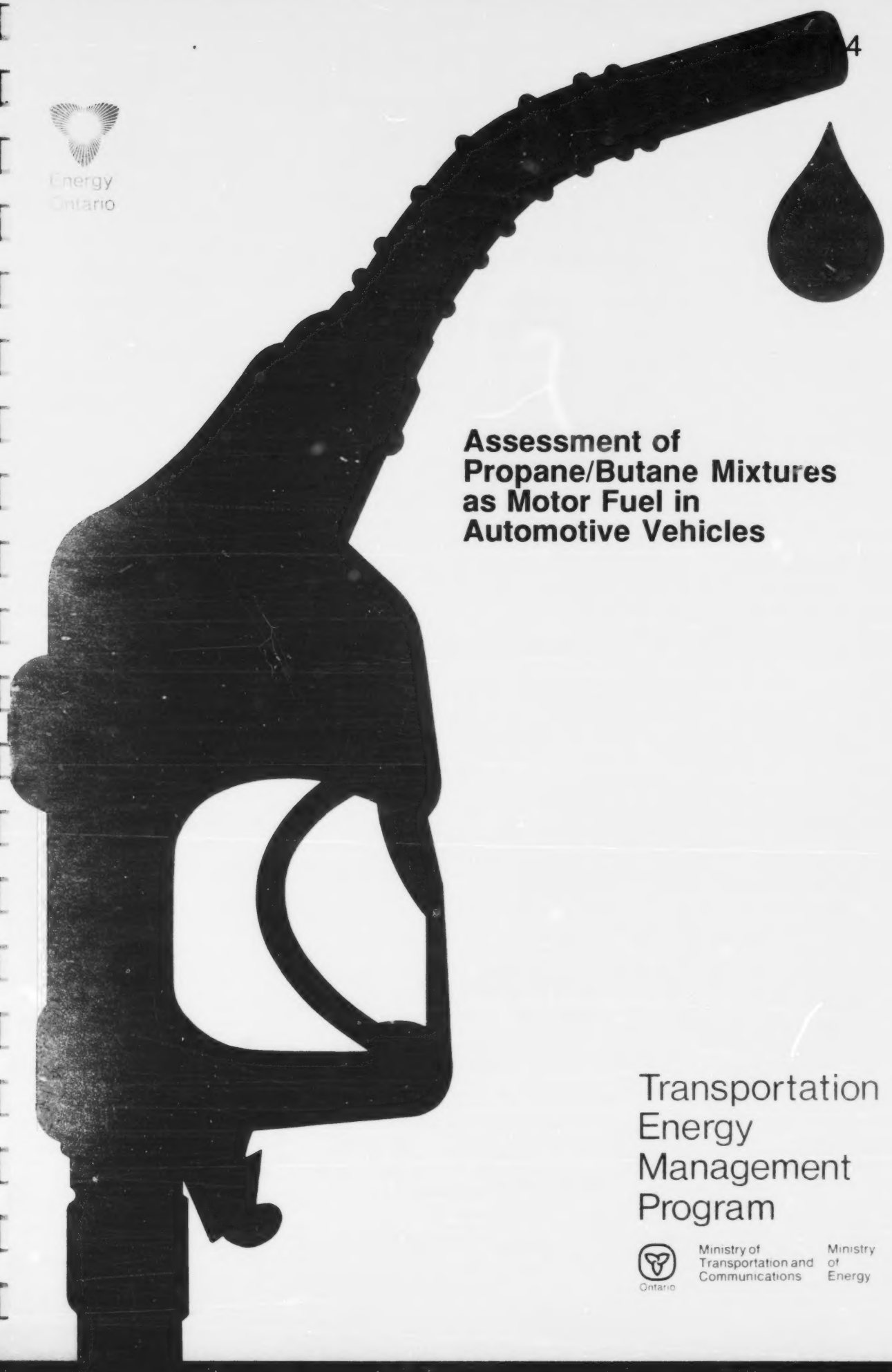

Assessment of Propane/Butane Mixtures as Motor Fuel in Automotive Vehicles

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Assessment of Propane/Butane Mixtures as Motor Fuel in Automotive Vehicles

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EXECUTIVE SUMMARY

A study has been made of the need and feasibility of augmenting the supply of automotive propane by the production of a mixed butane-propane automotive fuel, also called liquefied petroleum gas (LPG). The study also addressed the potential performance of vehicles using the new fuel, safety, and other key issues, including research, development, and engineering, which might be conducted to resolve the performance issue.

The supply of propane and butane extracted from natural gas at 160 plants in Canada now amounts to about 8.6 million m^3/year (4.6 million tonnes) and, from the refining of crude oil, about 3.3 million m^3/year (2 million tonnes), after the refiners' internal use of butane in the production of gasoline is deducted (about 2 million m^3 or 1.2 million tonnes in 1985). Both propane and butane supplies are substantially greater than the demand in Canada. The surplus currently exported to the US amounts to 40% of the propane supply and 56% of the net butane supply.

Canada's production of propane is likely to increase substantially in the period to 1995 and even beyond, and a shortfall in the supply for automotive use in that period is unlikely. Current demand for automotive use is at the 500 000 m^3/year level (19% of domestic demand) and is not expected to exceed 950 000 m^3 by 1995 (235 000 vehicles on propane at that time, 120 000 in use early in 1986), at which time exports of propane are expected to be at the 3.4 to 3.6 million m^3/year level. There is no urgent need, therefore, to develop a substitute for part of the propane used in automotive applications.

The domestic supply and demand for butane in the future is less certain and depends substantially upon the strategies adopted by refiners to meet the octane requirements of gasoline at the reduced lead level of 0.29 g/L in 1987 and a zero lead level in 1990 to 1992. The refiners appear to prefer to use conventional oil refining technology and limited use of a butane-based octane improver methyl tertiary butyl ether (MTBE) and, to some lesser extent, methanol-ethanol or methanol-butanol blends.

The anticipated outcome is that the net supply of butane will not increase substantially in Canada. The demands of the refining and petrochemical industry may increase somewhat, reducing the level of the export butane to perhaps only 25 to 37% of net butane production. Refiners report that high-level use of methanol without co-solvent butanol, or ethanol, in the production of unleaded gasoline in the future is highly unlikely, and large-volume addition to butane surpluses from this source is therefore unlikely.

No case can therefore be substantiated for the development of a new market for automotive butane at the expense of propane.

The price of the mixed butanes is currently 118 to 125% of the price of propane on a volumetric basis. No substantial change in the price relationship, which would create a demand for butane addition to propane, is anticipated. However, if such a price change were to occur it would be expected to increase the use of butane in the production of gasoline through blending, alkylate gasoline and MTBE production, or encourage the use of technology that is available for the conversion of butane to propane.

There is widespread use of butane-propane blends as automotive fuels in Europe. The permissible level of butane varies with the location and season. These variations in composition and LPG availability and the low-octane rating of LPG compared to the Canadian specification material have resulted in the almost total acceptance of dual-fuel vehicles in Europe, despite the reduced fuel economy of the dual-fuel configuration.

It would be uneconomical to encourage dual-fuel conversions in Canada to make a market for a low-octane butane-propane blend, especially since 90% of the current propane fleet has the more economic mono-fuel configuration. However, substantial difficulties are anticipated if a new grade of propane with a reduced motor octane rating is introduced for summer use:

- carry-over of the summer fuel to winter use, with an increase in the cold-start problems;
- a higher incidence of engine knock problems in marginally operative after-market conversions;
- an increase in the potential safety hazard of propane vehicles caused by the higher density and slower rate of dissipation of butane leaks and spills.

The report concludes that any reduction in the octane quality, cold-start performance, or safety of automotive fuel is unacceptable and that a proper target for fuel variation is to improve the cost, and performance, of propane vehicles, particularly their cold-start capability.

A program of fuel source selection, formulation, and testing, which can complement the investigation of improved propane engine hardware now under way at Chrysler Canada, is suggested. The fuel formulation program is expected to

- lead to increases in the gains in fuel economy and winter performance expected from the Chrysler program;
- increase public acceptance of propane vehicles; and
- result in compositions that contain high levels of butane that could be interchanged with HD-5 propane (Canada grade 1 fuel) for winter and summer should a need for butane use in automotive LPG develop in the future.

1/ INTRODUCTION

This report is presented at a time when crude oil prices in international trade have fallen to levels not seen since the mid-1970s, with crude oil freight on board (FOB) the North Sea and Arab OPEC (Organization of Petroleum Exporting Countries) ports currently quoted at US $14/barrel, and Alberta light crude oil priced for export at Canadian $18/barrel. The short-term future direction of price changes is also uncertain. With no restrictions now in place in Canada to prevent imports of crude oil and refined petroleum products or LPG (mixed propane and butanes), the effect of these new prices in the international market will be promptly felt in Canada by producers, refiners, distributors, and, eventually, end users of hydrocarbons. There is a consensus in the oil industry that, when oil production from non-OPEC sources, such as the North Sea and Alaska's North Slope, declines and reliance is again heavily placed on Arab OPEC oil supplies, crude oil prices will return to the US $25+/- barrel level, but there is no agreement on the duration of the current production overcapacity and low oil prices.

The glut of oil production capacity in OPEC and certain key non-OPEC areas reflects an immense achievement by the major non-OPEC oil-consuming nations brought about by three streams of activity:

1/ restriction of the demand for petroleum products achieved by the effect of high petroleum-product prices and government incentives and legislation to encourage oil conservation;
2/ replacement of oil-derived products by substitution of natural gas, coal, wood, and electricity;
3/ increases in the rate of discovery, development, and production of crude oil among countries outside OPEC.

The role that Canada has played in this effort to contain oil prices may never be documented, but it is certain that it could never have been achieved if many diverse programs by many nations had not been vigorously pursued.

The role of the hydrocarbon resource-poor province of Ontario in the development of oil conservation and distribution programs and practice is recognized, not only in Canada, but worldwide. One of the outcomes of the Ontario program has been the development of a market for alternative transportation fuels in the province, where some 50 000 vehicles now operate on propane and use of compressed natural gas and methanol-gasoline blends is increasing. The 55 000 vehicles that operate on non-petroleum fuels represent only about 1.2% of total Ontario highway vehicles but a higher percentage of the vehicles capable of operating on these fuels. Ontario's program of financial incentives to vehicle users

includes the remission of provincial highway fuel taxes on alternative fuels and of the sales tax on alternative-fuelled vehicles. In addition to these incentives, Ontario, through the Ministry of Transportation and Communications and the Ministry of Energy, often in co-operation with the corresponding federal government agencies, have supported the development of the physical and technical infrastructure needed to deliver the alternative fuels -- converted engines, vehicles, new refuelling facilities -- and legislation to ensure the safe operation of such vehicles and refuelling stations.

The rate of growth of propane use as a motor vehicle fuel has raised the issue of the adequacy of future supplies and the effect that supply constraints would have on the price advantage that propane enjoys relative to gasoline in Ontario and the western provinces. The issue of the supply of automotive propane is investigated in this report, together with the suggestion that has been made to expand the volume of propane by relaxing the Canadian motor fuel propane specification (CAN2-3.14-M78) to permit the addition of butanes to levels higher than the maximum of 2.5% now specified for automotive-grade propane.

Interest in the development of methanol as a gasoline extender has been increased by federal government legislation which requires that the level of lead additives in gasoline be cut by 60% from the current level. The presently permitted maximum level of 0.77 g of lead/L is to be reduced to 0.29 g/L by January 1, 1987. The federal government is now considering legislation to completely eliminate the use of lead in gasoline.

One of the many ways in which the octane level of gasolines can be maintained in the presence of reduced quantities of lead and in lead-free gasolines is through the addition of alcohols such as methanol. However, addition of methanol to a gasoline to extend the volume of fuel or to improve its octane rating reduces the quantity of butanes that can be blended into the gasoline. It has been argued that if the use of methanol (and ethanol) in gasoline were to become significant, then a surplus of butanes might develop which could be ameliorated by their incorporation in a new grade of automotive propane. Despite the wide use of LPG in Europe and parts of the US, little is known about the performance of such blends in Canadian vehicles in the demanding Canadian environment, and even less, about the economics of producing and distributing the new automotive LPG within the present infrastructure.

These issues and concerns regarding propane supplies and their augmentation with butane are the subject of this report.

The need for an investigation of propane blends was noted by Chrysler Canada Ltd. in its 1984 report prepared for Transport Canada's Transportation Development Centre. The report describes developments needed to improve the commercial prospects and performance of propane-fuelled light vehicles (automobile, vans). It is an excellent review of the state of knowledge on propane use in vehicles and, in particular, of the performance improvements needed. Based on the Chrysler analysis and its experience with the manufacture and marketing of mono-fuel propane vehicles, Chrysler is undertaking a research and development program involving

- optimization of the mono-fuel propane engine, and
- design and testing of a dual-fuel (propane-gasoline system).

Chrysler proposes to investigate the performance of selected propane-butane blends if their production, distribution, and use appear to be practical and economic.

An early application of the present investigation is therefore to provide information that may assist Chrysler in its go/no-go decision on the testing of propane-butane blends.

2/ OBJECTIVES OF THE INVESTIGATION

1/ To investigate the need for augmentation of the automotive propane supply by the production of a mixed butane-propane automotive fuel, also called liquefied petroleum gas (LPG).

2/ To investigate the feasibility and economics of producing and distributing such blends in Canada.

3/ To investigate the potential performance of vehicles fuelled by butane-propane blends in comparison with those fuelled by the present specification-grade of propane.

4/ To identify the key issues that require resolution before the blends can be introduced and to define the subset of issues that can be resolved through research and engineering effort.

5/ To provide and support an opinion on the feasibility and benefit of butane-propane blends as automotive fuels in Canada.

3/ METHOD OF APPROACH

An automotive-grade LPG would be a new grade of propane in Canada, not a new product. The new grade will be accepted by the fuel distributors, manufacturers of vehicles and conversion kits, and by vehicle operators only if

- supplies of automotive propane to the present specification are inadequate,
- use of the new grade is transparent to consumers but cost-effective to suppliers, and
- use of the new grade provides a cost advantage sufficient to offset its disadvantages.

The method of approach used in this investigation, therefore, concentrates upon the need for butanes in automotive grades of propane and the costs of introducing and using the new grade in Canada in the period to 2005. This involves examination of the complex interaction of fuel supply, demand, price, and market share illustrated in Figure 1. The supply of the new fuel is related to the resource available, by the level of production of LPG from Canada's refineries and gas plants, and by imports, all being conditioned by the level of production of gas and petroleum products. The supply of the new fuel is related also to the surplus of propane and butane that exists to serve the new transport fuel market when the demands for propane and butane are met in more conventional applications, such as the heating fuel, petrochemical feedstock and solvent flood (enhanced oil recovery processes), and export markets. The keys to the share of the automotive fuel market which the LPG grade will achieve are the price of the fuel relative to competing products (current specification propane, gasoline, diesel, and compressed natural gas [CNG]); the efficiency, performance and user perceptions of vehicle performance; and the availability of the fuel at times and locations convenient to the users.

4/ THE SUPPLY OF PROPANE AND BUTANES

4.1/ The Origin of Propane and Butanes

Propane and the two butanes -- normal (n-butane) and iso (i-butane)-- occur together with varying proportions of the lighter hydrocarbons (ethane and methane) and heavier hydrocarbons (pentanes and condensate) in unprocessed natural gas and in the light products from the refining of crude oil. These are the current commercial sources of propane, butanes, and LPGs, commercial grades of which also contain traces of higher and lower hydrocarbons. LPG is produced but not recovered in the processing of tar sand bitumens and heavy-oil upgrading and could be produced with heavier hydrocarbons by the liquefaction of coal. These are future higher cost, contingent supplies.

4.2/ International LPG Trade and Canada's Position as a Supplier

LPG is a minor component of world and Canadian energy markets. The non-communist-world (NCW) production of LPG in 1984 totalled about 91 million tonnes (about 150 million m^3), of which 60% was propane and 40% butanes. This LPG production is only about 4% of the NCW production tonnage of crude oil and 2.7% of the combined NCW production of oil and gas. The NCW supply of LPG (after allowances for internal use in gas and oil recovery operations) is currently divided into that which originates from the refining of crude oil (34% by weight), the processing of natural gas associated with crude oil recovery (21% from associated and solution gas), and the processing of non-associated natural gas (45% of the NCW production). In contrast, only 20% or so of Canada's LPG production of about 6.7 million tonnes/year originates from oil refining, showing the importance of natural gas use and exports in the Canadian economy and the inroads made by natural gas into refined petroleum product markets.

The Canadian LPG export market is extremely important. In 1984 exports of about 3.9 million tonnes of LPG generated export earnings of $1.1 billion ($0.97 billion after allowance is made for LPG imports into Canada). A significant proportion of this export revenue is generated by the export of Alberta LPG processed into propane and butanes shipped from the Sarnia, Ontario LPG fractionation plant owned and operated by Dome Petroleum and Amoco.

Canada's exports of LPG to the US have been consistently in the region of 3.5 to 4 million tonnes/year, but may be subject to more intense supply and price competition in the future from US supplies of LPG and petroleum products and, in particular, from the large surplus of LPG capacity now

in place in the Middle East, and scheduled to come on stream in Algeria, the North Sea (UK), Australia, Indonesia, and Thailand.

Since a major portion of the LPG production is obligatory product, it must be sold in a market clearing operation, or the wet gas-containing LPG, flared or re-injected into oil reservoirs. While oil is being pumped and associated and solution gas produced, there is a rationale for operating LPG recovery plants and exporting the product, even when producer netbacks on LPG provide a meagre return on the sunk capital investments after operating costs of recovery are met.

The total NCW production and sale of LPG grew from 67 million tonnes in 1970 to 76.6 million tonnes in 1975 and 91.0 million tonnes in 1984. Industry forecasts that production from gas processing and oil refining in the NCW will reach 125 million tonnes in the year 1990, an almost 40% increase over the 1984 level. Some 15 million tonnes, or 12% of this production, will need to be absorbed in new markets. The surplus of supply over demand in conventional markets will originate predominantly in the Middle East, and the surplus that cannot be converted there to petrochemicals (such as ethylene and methyl t-butyl ether) will be exported by ocean tanker.

The large markets in Japan and the US will be particular targets, and new volumes will be placed in cost-sensitive petrochemical markets. The exporters' netbacks from these sales will absorb the ocean freight, such as the US $26 to 28/t(tonne) ocean freight charge that now exists for shipments from Saudi Arabian ports to the main US import terminal for LPG at Mont Belvieu, Texas, and $20/t from Algeria to Mont Belvieu. The freight charges are tied, in part, to the cost of number 6 fuel oil to the ocean tankers and, hence, to the price of crude oil.

The conclusion relevant to Canada with respect to this world surplus capacity for LPG is that Canada's export markets in the US will be under price and supply pressure for at least the remainder of the decade and exports to Japan, which have already been lost to Middle East producers, are unlikely to be regained at profitable prices. This adds substance to the Canadian effort to increase the use of propane as a vehicle fuel in Canada and replace much of the naphtha used for the production of petrochemicals by butanes and propane. It is possible that Canadian production of LPG in the short term may be curtailed in the face of increased Arab OPEC oil and associated LPG production and aggressive pricing of both. LPG prices in Canada's export markets have already begun to respond to this competition with propane prices at Mont Belvieu recently at the 22 to 23 US¢/US gal. level (9.25 Cdn¢/L). LPG prices may drop lower in the medium term if OPEC exporters adopt the same netback basis

policies for their propane and butane pricing as they have for crude oil and refined petroleum products.

4.3/ Current Canadian Supplies of Propane and Butanes

Figure 2 illustrates the factors affecting the supply and demand for LPG in Canada. The recent history of production of propane and butanes beyond the requirements of the refineries and gas plants in Canada and Ontario is summarized in Table 1.

The details of Canada's supply and demand for propane and butanes are given later in this report, but here it can be noted that the combined supply of propane and butanes available to Canadian and export markets has increased by 10% over the period 1975 to 1985, whereas Canadian consumption of these commodities has increased by 37% in the same period (Table 2). The increase in demand has resulted in a curtailment of exports. In 1985 LPG exports were at the 23 400 m^3/day level (7600 m^3 of propane and 6200 m^3 of butanes), which was 43% of Canada's marketable supply; in 1975 exports stood at 54% of the marketable LPG supply. The LPG export volumes represent a large source that can be tapped if high-value uses for LPG can be developed in Canada, such as the carburetion market. LPG exports are sufficient to fuel at least two million vehicles, 16 to 17 times the current 120 000 propane highway vehicles.

5/ PROPANE AND BUTANES FROM NATURAL GAS

5.1/ Sources of Supply

Propane and butanes are generally a by-product of natural gas processing and crude oil refining. In Canada the supply of marketable LPG from gas plants is larger than that from refineries, since the latter have substantial internal demand for butanes, which, in certain refineries, will exceed the level of butanes produced in the refining processes. The supply of LPG from gas plants is discussed in terms of the supply from

- existing plants
- processing of new, but conventional, sources of natural gas
- frontier sources

5.2/ Conventional Supplies of LPG from Natural Gas: The Current Position

Data on Canadian LPG supply are available from National Energy Board (NEB) publications (e.g., "Canadian Energy Supply and Demand," 1984 and "Production Disposition Summary Reports") and from industry sources (e.g., a joint publication by representatives of Esso Resources Canada Ltd., Chevron Resources Ltd., and Amoco Petroleum Co. Ltd. in the October 1985 issue of Propane Canada). The NEB monitors 99% of Canada's production from natural gas processing plants on a pool-by-pool and associated-gas-plant basis and has a computer-based model which predicts changes in propane and butane yield occurring with depletion of the gas reservoirs, in the volume of cycled gas (gas re-injection into reservoirs after extraction of the natural gas liquids), and in the recovery efficiency of processing plants.

The natural gas processed may originate from oil reservoirs (this is the so-called "associated gas") and be processed in the field. Other field plants recover natural gas liquids from non-associated gas reservoirs. The field plant processing is essential to remove contaminants (water, hydrogen sulphide, and carbon dioxide) from gas and to reduce the dew point of the gas to the point where it can be pumped through pipelines without separation of natural gas liquids (propane, butanes, pentanes plus), which would present safety problems in the pipeline and at gas compressor stations. The removal of propane and butanes to the dew point level for gas transmission is therefore obligatory.

It has been estimated that 25% of the gas-derived LPG is non-discretionary and this level of LPG extraction from natural gas must continue regardless of the economics of the LPG market. However, LPG extraction is normally quite profitable, and production of non-obligatory, or so-called discretionary, product is at levels which

remove, on average, over 85% of the propane and even higher levels of butanes from Canada's natural gas. These levels of extraction are achieved through use of field and straddle plants which are located on the main gas trunk lines and which reprocess field-treated gas to extract ethane, propane, and butanes (and some remaining pentanes-plus components).

The production at field plants is normally a natural gas liquids mixture which is shipped outside the gas-producing area by pipeline, rail tanker, and even road tanker for fractionation to specification grades of propane, mixed butanes (so-called field butanes), or to a mixed LPG. Sixty-five percent of natural-gas-derived propane and butanes are produced in the field plants processing associated and non-associated gas. The six straddle plants located on the main gas transmission lines at Empress and Cochrane in Alberta produce mixed LPG (Petro-Canada at Empress) or specification propane and butanes. These plants produce about 34% of the propane derived from natural gas and 28% of the total marketable propane produced in Canada from all gas plants and refineries.

A challenge to the straddle plants has recently emerged with the start-up of a number of specialized field plants that produce a mixture of ethane (predominantly), propane, and butanes, solvents which are injected into partially depleted oil reservoirs and serve to assist in the solvent flood recovery of crude oil. These "deep-cut" plants deplete the gas liquids content of the natural gas, which is delivered into the main natural gas pipelines and will eventually influence the liquids recovery levels at the existing straddle plants. The deep-cut solvents are temporarily lost to Canada's propane and butanes supply, but a high proportion of the gas liquids will be recovered, and miscible flood operations will become a net source of propane and butanes in the mid to late 1990s. Up to 66% of the gas liquids injected are expected to be recovered with a composition 55% ethane, 35% propane, and 10% butane, illustrating that the only butane injected is that recovered in deep-cut field plant operations and not separated from the bulk of the gas liquids, whereas solvent flood gas liquids purchased from straddle plants are unlikely to contain valuable butanes.

The combination of 154 field and six straddle plants in Canada produced about 5.4 million m^3 of propane and 3.2 million m^3 of butanes in 1984, a total of about 4.6 million tonnes of LPG. Not all this product is available for sale to conventional markets. Some 830 000 m^3 of propane and 330 000 m^3 of butanes were contained in the mixes with ethane fed to solvent recovery processes in 1984. These volumes accounted for about 15% of the gas plant production of propane and 10% of gas plant butanes production in the year. The remainder of the gas-derived propane and butanes are marketed by a relatively small number of companies engaged in

the wholesale trade to export markets (principally, shipments of separated specification products to the US) and to domestic markets (which receive LPG mixes and specification products).

A most important feature of the distribution system for central and eastern Canada and contiguous US regions is the ownership by Dome and Amoco of the Edmonton LPG terminal and Sarnia LPG fractionation plant, which currently control LPG access to the common carrier multi-product pipeline owned and operated by Interprovincial Pipeline Ltd. Companies wishing to ship LPG to the central or eastern regions of Canada and the US must choose between rail tanker shipment or sale of product to Dome/Amoco and re-purchase of product (LPG or fractionated specification grades) from Dome/Amoco in Sarnia. The high degree of control of LPG transport afforded to Dome/Amoco by the innovative investment and business operation may account, in part, for the 3.5¢/L wholesale price differential that exists between butanes (and the 2.6¢/L differential for propane) in Sarnia and Edmonton, where the Alberta crude oil differential for these locations is about 0.65¢/L. The Sarnia facility is designed to process 100 000 barrels per day (BPD) of natural gas liquids in three trains and is capable of processing about 50% of Canada's LPG. Products shipped from the Sarnia facility are propane and separated butanes (normal and iso), which are shipped principally by rail tanker to US and Canadian markets or by road tanker within 1000 km of the plant.

A major disadvantage in Canada at this time is the lack of low-cost pipeline capacity suitable for the movement of propane and butanes east of Sarnia, the effect of which is a high cost for the rail transport of propane and butanes to market in eastern Ontario, Quebec, and the Atlantic provinces, limiting the development of the automotive fuel and other markets for propane and butanes in these areas.

The yield of natural gas liquids is changing over time as the proportion of oil-associated gas in the natural gas pool decreases due to the continuing decline in production of light crude oil in Alberta. The NEB estimates that the gas liquids yield from natural gas will change from the current level of about 92 m^3 of propane and butanes/million m^3 of gas processed to 72 m^3 from additional supplies from reserves not yet tapped. The ratio of propane to butanes in Canadian natural gas will remain within the 1.6 to 1.7 range, and the butanes mix will continue at 70% normal and 30% isobutane. The market demand for the two isomers of butane may not be satisfied by this natural ratio. In the future, using existing technologies (Dome has such a facility within the Sarnia plant), the lower volume n-butane will be converted to the supply-limited isobutane isomer. The isomerization process is already operated in the US to meet the refiners' demand for the valued isobutane as a feedstock for the

production of the octane booster, alkylate.

5.3/ Future Supplies of Propane and Butanes from Canadian Natural Gas

The bulk of Canada's future supplies of marketable propane and butanes will continue to be from the processing of natural gas from conventional areas and from the refining of crude oil, possibly augmented by new supplies generated from the processing of frontier gas, some associated with frontier oil (offshore) developments, others with expansion of natural gas production to frontier sources.

In the future, production of LPG from gas plants will track natural gas production, with a slow reduction in the yield of propane and butanes encountered over time. As present gas cycling schemes are completed (which are stripping gas liquids from gas to re-inject into gas or oil reservoirs), the butane and propane content will decline in the gas streams as the proportion of solution gas (associated gas) is reduced. However, the effect of these changes in the composition of natural gas on the production of propane and butanes is likely to be small compared to the variations which can occur in the production of natural gas.

The NEB forecast of 1984 anticipated natural gas production in Canada to increase in the near term and to decline gradually thereafter until the year 2002 when exports to the US are terminated. The extraction of propane and butanes from these conventional gas volumes, according to the NEB, would peak in 1990 at 33 700 m^3/day and decrease thereafter, reaching the 21 900 m^3/day level by 2005. The 1990 level of LPG production from these sources in 1990 would be 126% of the 1983 level of 26 700 m^3/day; the level in 2005, only 82% of the 1983 level.

Although the production of LPG from associated gas is projected to decrease steadily to about 75% of the 1983/1984 levels in 1995, there is a good chance that new sources of associated gas will be available from offshore oil recovery operations in the Atlantic region. This could come from the Hibernia oil field off the coast of Newfoundland, from the newly discovered oil field found south of Sable Island, and the Venture gas field off the coast of Nova Scotia. However, the rate of investment in discovering and developing these new oil and associated gas resources may be changed if the current low price for crude oil continues. These associated sources could be important to Canada's LPG supply, since associated gas is a rich source of LPG (commonly liquid gas yields are two to three times that from unassociated gas). The supply would be strategically located to serve areas where the price of propane and butanes is determined by the high cost of product transported to the region by rail from Edmonton or Sarnia.

Generally, oil recovery is accompanied by 2.5% by volume of propane and 1.5% by volume of butanes, so that a minimum size recovery of crude oil from the Hibernia field of 150 000 BPD would generate 350 000 m^3/year or 6000 BPD of LPG, about 6% of the current level of LPG production in Canada from all sources.

The production of propane and butanes from the Venture gas field off the Nova Scotia coast could also be a source of LPG in the 1990s, but exploitation of this source is not certain, because of the high cost of service estimated for the gas pipeline and the low gas netback anticipated at prevailing gas export prices. Mobil Oil has estimated that a gas liquids plant processing gas from the Venture field would produce some 1300 m^3/day of propane and 780 m^3/day of butanes at the peak output achieved three to four years after start-up, if high recovery of gas liquids were justified, or approximately one-third of the level if it were considered necessary to leave the discretionary volume of products in the gas to increase the limited volume of gas available for marketing in the US.

The Venture field could therefore provide between 760 000 m^3/year and 250 000 m^3/day of LPG in the mid-1990s or at a time when natural gas could be exported at a price in excess of $4.50/GJ. There are other frontier gas and gas liquids recovery prospects in the MacKenzie Delta-Beaufort Sea region capable, according to Imperial Oil, of being produced by 1996 to provide gas and 330 000 m^3/year of propane and 180 000 m^3/year of butanes, should gas demand and economics provide a rationale for accelerated development. Other frontier sources of LPG from associated gas are unlikely to be tapped in the next 15 to 20 years, since the gas and gas liquids associated with these remote crude oil sources would no doubt be re-injected to maintain reservoir pressure and increase oil recovery.

The range of values forecast for the production of propane and butanes from the processing of associated and non-associated conventional natural gas, additions from reserves, and frontier gas sources in the period to 1995 and in 2005 is summarized in Table 3. The forecast is for a substantial increase in the supply of both gas-derived propane and butanes for at least a 10-year period, with a return to current production levels by 2005. The turndown in production forecast by the NEB reflects the board's conservative approach to estimates of gas reserve additions and future deliverability: a recent industry forecast of propane supply for 1995, for example, is 10% higher than that from the NEB.

Notwithstanding these differences, the following is clear:

1/ Propane and butanes supply from gas plants will increase substantially in the next 10 years with the increased level of demand for natural

gas, particularly in the US export market where the current gas surplus will be taken up.

2/ Large blocks of propane and butanes are non-discretionary and must be produced to condition the residue gas for gas transmission. Non-discretionary removal probably accounts for 4000 m^3/day of propane and a similar volume of butanes, or 30 to 33% of the total LPG supply and 50 to 60% of Canada's domestic LPG demand.

3/ Discretionary production of propane and butanes and production from frontier gas is dependent on the price of propane and butanes relative to competing petroleum products (heating fuels and gasoline) and, in the case of frontier supplies, on the domestic and export price of natural gas. Intense competition from low-cost petroleum products from low-cost crude oil will delay frontier gas and LPG production and may somewhat reduce discretionary LPG production elsewhere.

4/ Long-term continuation of low crude oil prices will, first of all, reduce the demand for miscible flood volumes and then, later, the volumes of LPG recovered from the associated gas and oil.

5/ For planning purposes, the lower bounds of supply given in Table 3 are appropriate.

6/ LPG PRODUCTION FROM REFINERIES: THE CURRENT AND HISTORIC POSITION IN CANADA

6.1/ Background

The Canadian refineries produce large volumes of propane and butanes but are also major users of the latter. Thus, propane is available from refineries on a year-round basis, but overall, the refineries are net purchasers of butanes from gas plant production.

The production of propane and butanes in the refining process is a retrograde step, since historically the refiners' netback on the sale of propane and butanes has not recovered the value of the crude oil from which they originate. In the period 1976 to 1984, for instance, the ratio of the cost of crude oil to refiners in Edmonton to their netback from wholesale sales of butanes was 1.26 on a volume basis, the ratio for crude costs to propane wholesale prices being 1.77. Where butanes can be blended or converted into gasoline there is an incentive to the refinery to maximize the use the use of butanes within the refinery and even to purchase gas plant butanes for this purpose. Since the refinery has no internal use for propane, which requires high-cost storage facilities, it is sold in a market clearing operation as produced at a low realization, the price received by the refiner being determined by the larger volumes of gas-derived propane which are marketed in competition.

Propane and butanes are contained in the crude oil purchased by the refiners and are driven off and recovered in the simplest refining process of distillation. The dissolved LPG recovered in this step varies with the type of crude oil purchased, ranging from 5% or so of the crude oil volume for typical Canadian (Alberta) light crudes, to 1.5% or so from Canadian heavy oil, to 2% from Arabian light crude oil, and up to 3.5% from Arabian heavy crudes. Synthetic crude oil from the Suncor and Syncrude tar sands bitumen processing plants has already been distilled and therefore contains little, if any, dissolved propane and butanes.

Propane and butanes are generated by the high-severity refining processes which alter the chemistry of the crude oil, such as processes which increase the aromatic content -- the reforming of naphtha to an aromatic high-octane gasoline blending stock -- or those that crack heavy fractions to increase the yield of distillates, which include catalytic cracking, visbreaking, and hydrocracking operations. The cracking operations that do not involve concurrent hydrogenation (i.e., catalytic cracking operations) produce unsaturated reactive propylene and butylenes in addition to propane and butanes. Propylene and butylenes are used in the refinery to produce high-octane synthetic gasolines (alkylate or

polymer gasolines) or are recovered for sale to petrochemical companies where refineries are operated to produce aromatics (benzene, toluene, xylene) for sale. Synthetic gasoline production from propylene and butylenes becomes an important means to maintain gasoline octane quality. The production of alkylate from propylene or butylenes also requires isobutane as a co-reactant, and this accounts for the bulk of the refiners' need for gas plant butanes and for the 1¢/L or so premium in the wholesale price that isobutane commands in comparison with the less reactive n-butane or mixtures of butanes ("field butanes").

Normal butane has a major use in gasoline too. Specification-grade or field butanes are blended into gasolines to provide front-end fuel volatility. Because of the low-cost, relatively high octane value, and availability of n-butane, these butanes are blended up to the maximum permitted by the gasoline specifications on maximum vapour pressure and minimum octane values. The amount of butane that can be used to formulate gasolines is governed by the weather, the vapour pressure, and the octane value of the components needed to produce specification grades of unleaded regular, unleaded premium, and leaded regular gasolines.

From the foregoing it will be obvious that there is no "typical" Canadian refinery. Each has a different feedstock composition, different slate of products to market, and different equipment configurations, ranging from simple skimming-type refineries which "top and tail" crude oil to produce distillates and large volumes of heavy fuel oil (or asphalt), to complex refineries that process crude oil to the highest value fuels and petrochemicals, to the unique refinery at Scotford, Alberta, which was designed solely for the refining of synthetic crude oil. Even within similar refineries, different strategies will be followed for operating the process units and for blending streams to produce the required product slate at minimum cost.

6.2/ LPG Production and Demand in Canada's Refineries

Table 4 illustrates the LPG balance in a refinery that is principally operated to convert light crude oil and purchased condensate to fuels.

Propane and the two types of butanes originate in the crude distillation and reformer units. The fluid cracker also produces these, together with propylene and butylenes. In this refinery, propane and propylene are sold, with the seasonal surplus used as fuel in the refinery. The isobutane and butylenes appear in gasoline through direct blending with other fractions and are combined in the form of refinery alkylate. N-butane is used to pressurize the gasolines, and the total butanes requirement exceeds production, so fixed butanes are purchased to 2% of

the volume of crude oil processed.

This "simple fuels refinery" therefore converts about 11% of the crude oil to propane, butane, propylene, and butylenes but exports propane (2% of crude volume), propylene (1% of crude volume), and a small volume of a mix of propane and propylene (0.2% of crude): total C3 hydrocarbon exports, 3.2% of crude volume.

Table 5 illustrates a more complex refining operation that produces propane for sale (and use as a refinery fuel when surplus exists) but also large volumes of benzene, toluene, and xylene. This reduces the volume of unleaded gasolines produced per unit of crude and requires more complex cracking operations (including a hydrocracker unit to complement the fluid cracker) and the production of both polymer gasoline and alkylate to reach the required octane levels in the gasoline, since the aromatics content is reduced by the removal for sale. Such a refinery would not require import of butanes and would be able to store and market its surplus n-butane to other refiners. The higher severity crude oil processing increases the yield of C3 and C4 hydrocarbons to 12% of the crude oil processed, but sales of propane and n-butane together amount to only 1.3% of the crude processed.

Overlaid on these variations in the net production of butanes and propane because of differences in equipment and products are other seasonal and location factors that also affect the butane and propane balance.

1/ Seasonal variation in refinery crude oil throughput is necessary to meet the peak demand for gasoline in the summer months and for fuel oils in the winter.

2/ Seasonal variations must be made in the composition of gasolines to provide vapour pressure control to facilitate cold engine operations in winter and to prevent vapour lock in summer. This principally involves regulation of the composition of the gasolines to meet the vapour pressure specifications set by the Canadian Government Specifications Board (CGSB) measured by the Reid vapour pressure (RVP) and is achieved mainly by varying the volume of butanes blended into the gasoline:

	Max. RVP (psia)
November-February	14.9
March and October	13.9
April	13.0
May-September	11.0

3/ Variations in the composition of unleaded regular and premium grades and the leaded regular grade of gasoline are necessary to meet the octane number limits also set by the CGSB.

4/ The market share of gasoline with respect to distillates is shifting, and, in particular, the market share of diesel fuel is increasing.

Seasonal refinery throughput is illustrated in Figure 3. Refinery production of both propane and butanes tracks the crude runs, but since net production of butanes is also determined by internal use, it does not track crude runs (Figure 4).

Vapour pressure control: Table 6 illustrates the effect of season on the blending of butane in gasoline by reference to a fuels refinery producing unleaded regular and leaded regular containing the average level of lead octane enhancer used in leaded grades in Canada in 1984 (0.49 g of lead/L) blended to meet the summer vapour pressure and octane specifications of CGSB. The refinery would process a mix of light crude oil, heavy crude oil, syncrude, pentanes-plus, and condensate from Alberta and seasonal volumes of butanes to produce refinery fractions that can be blended to produce gasolines. These are principally light straight-run gasoline fractions from the fluid cracker and reformer units, polymer gasoline, alkylate, and n-butane. One economic solution to using these fractions to produce specification gasolines, illustrated in Table 6, involves the blending of 9.3% by volume of n-butane into the unleaded gasoline and 6.3% by volume into the leaded regular grade.

Calculation of the maximum n-butane content that can be used with these blending stocks to meet the CGSB season standards shows that the maximum volume of n-butane that can be used occurs in the winter period and the minimum in the summer but, also, that the proportion which can be used in the leaded gasoline (with a high level of volatile low-octane light straight-run gasoline permitted because of lead addition, which increases the octane) is lower than that in the unleaded grades, where low-volatility cracked and reformed blending stocks must be used to achieve octane specifications.

In the refinery example used, the level of n-butane that may be incorporated into the unleaded grade reaches almost 16% of the gasoline volume in the winter months, and 13% by volume may be incorporated in the leaded graded in the same winter period. The volume of butanes included in the in the alkylate (derived principally from i-butane and butylenes) increases the winter-grade level of butane incorporation in the unleaded regular grade up to 40% or so of the total gasoline volume. The leaded regular grade, on the other hand, with no requirement for alkylate, may

therefore contain only the 13% by volume of butane required for vapour pressure adjustment and no chemically bound butane.

The summer grade of regular unleaded gasoline may be blended with up to 9% by volume n-butane; the leaded, to only 6.5% by volume. Even in summer, the unleaded gasoline may still require an additional 30% of chemically bound butane in the form of alkylate to meet octane specification, but in this example, the leaded gasoline will not require alkylate for that purpose.

While other refineries will have different strategies for meeting the octane requirement of unleaded grades which may not require such large reliance on butanes, it is clear that

1/ there is a huge demand for both n- and i-butanes in Canada's refineries;
2/ demand for n-butane is highly seasonal;
3/ demand for i-butane for the production of alkylate is less dependent on the season but tracks refinery crude oil runs; and
4/ one major route to meet octane requirements of unleaded gasolines is through the production and intensive use of alkylate.

Alkylate production creates a large demand for butylenes and, increasingly, for refinery propylene to react with i-butane. Unleaded gasoline sales in Canada are approaching 43% of total gasoline sales: further growth in the proportion of unleaded gasolines, the introduction of high-octane premium unleaded, and legislation effective January 1987 to contain the lead level of leaded grades to 0.29 g/L will increase the demand for high-octane gasoline blending stocks. Alkylate demand and, hence, i-butane demand will therefore increase in the future.

6.3/ The Effect of Crude Oil and Product Quality Changes in the Period to 1985

The trend to processing heavier grades of crude oil and operation of units at higher severity (to offset the reduced use of lead in gasolines) and the increased levels of recovery of propane and butanes (because of their increased value) led to a doubling of the reported butanes production in the period 1979 to 1985 to the 1985 level of 5000 m^3/day. This was a period in which the volume of crude oil and condensate processed in the refineries decreased by 23% to the 1985 level of 216 000 m^3/day. Propane production and recovery was static in the period at 4200 m^3/day. Only a part of this output was made available for sale: the net availabilities from the refineries in 1985 were reported at about 3600 m^3/day for propane and about 2600 m^3/day for butanes (n-butanes in summer, principally).

Note that the level of production of butane and butylenes in the refineries, the reported output of n-butane for sale, intra- and inter-refinery transfers, and the purchase of gas plant butanes complicate the interpretation of the volume of butanes that may be available from the refineries to a new use, such as automotive LPG.

6.4/ Future Supply of Refinery LPG in Canada

6.4.1/ The Trends

The most important factor which will determine the LPG balance in Canada's refineries in the period to 2005 is the impact of the phase-down and eventual phaseout of the use of lead alkyls as octane improvers. Other significant factors are the changes in the volume of crude oil refined, the quality of the crude mix, the effect of imports and exports of refined petroleum products, and the potential for recovery of LPG from the off-gases produced with syncrudes in the processing of tar sand bitumens and heavy oil.

6.4.2/ The Effect of Refinery Runs on Future LPG Supplies

The NEB 25-year forecast of Canadian energy supply and demand made in 1984 projected a continued decrease in the demand for petroleum products and crude to Canada's refineries to about 1995, after which a modest growth was considered likely to boost refinery crude runs back to 1985 levels by 2005. Without adjustments for changes in crude quality and gasoline specifications, NEB predicted that the net supply of propane and butanes from refineries would parallel crude processed. Forecasts (in 1985) by representatives of LPG producer groups with refinery and gas plant operations have somewhat higher volume estimates for the period to 1995 for refinery propane production, which, in Table 7, have been used to calculate a butane production forecast.

Forecasts (in 1985) of the volume of crude oil processed in Canada's refineries and attendant propane and butane production may now need revision to reflect the increased demand for crude oil that will follow reductions in the price of crude oil and petroleum products, begun in 1986, but may be offset by increased taxation.

After the large savings in gasoline consumption that have been achieved by vehicle, and particularly engine downsizing, it is difficult to see more than a 10% increase in gasoline and other transport fuel consumption from potential price changes. Electric plants and domestic furnaces converted to coal and gas, respectively, are unlikely to reconvert. Hence, an upper bound of possibly +5% is estimated on the butanes and

propane production increases that will result from reduced oil costs to Canada's refiners.

On the negative side, there is a warning from the doubling of finished petroleum products imports into Canada in the period 1983 to 1984, and from even greater increases in the US, that imports of refined products could reduce refinery runs in Canada and the level of production of refinery propane and butanes.

Recent investigations of the costs of LPG imports into eastern Canada compared to current costs of propane and butane shipped by rail from western Canada indicate that imports of this commodity would bring cost savings to the Atlantic region and Quebec. LPG imports would affect the level of recovery of propane, at minimum, in the two refineries of Nova Scotia (Imperial and Texaco in Dartmouth); in the Irving Oil Company refinery in Saint John, New Brunswick; imports of butane from Alberta and Sarnia to the Atlantic market; and the Quebec petrochemical industry (Petromont, Montreal).

In the period to 2005 it is likely that oil production will be under way from Hibernia and, possibly, offshore Nova Scotia. The production of propane and butanes from the associated gas recovered with the oil has been included in the forecasts for gas processing for propane and butanes given in Section 5.3.

How much of this oil will be processed in Atlantic region refineries is not certain, but if a proportion of the new oil resources was processed to provide exports of finished products in addition to the volumes used to displace current imports, then additional supplies of refinery propane and butanes would be available. These would be strategically significant, since about 250 m^3 of propane/day is currently imported from western Canada at high cost into the Atlantic region to meet the seasonal heating requirements that cannot be met by the 200 m^3/day supply from the region's refineries. With the changed circumstance of low-cost imported oil, the development of the offshore Atlantic crude oil and gas resources may be delayed and, with it, the potential for new sources of propane and butanes.

It has been estimated by the NEB and involved oil companies that the off-gases from the synthetic crude oil and heavy oil upgraders in Alberta, and planned for Saskatchewan, could be important future sources of butanes and propane. The levels of recovery would be dependent on the economics of operating the new recovery facilities and the netback received on the new propane and butanes supply.

At high-incentive prices, Dome estimated the following potential new supply from syncrudes production and heavy oil processing:

	1990	1995
Propane m^3/day	3310	6310
Butanes m^3/day	300	575

The required investments will not be made and potential volumes will not be produced in the current oil, propane, and butane price environment.

6.4.3/ The Effect of Lead Removal on Refinery LPG Supply

Numerous studies of the impact of lead phase-down and lead elimination from Canadian gasoline have been made. The consensus follows:

1/ Phase-down of lead levels in leaded grades to the 0.29 g/L level will increase the clear road octane requirement of the entire gasoline pool by 2.5 to 3.0 octane numbers. (Clear octane refers to the octane required without octane-enhancing additives such as tetraethyl lead or methanol).

2/ Total phaseout of lead would increase the clear road octane requirement by a further 3.5 to 4 units.

3/ The lead levels legislated for 1987 can be accomplished by Canadian refiners with no great investment and without the use of oxygenated octane enhancers such as methanol. Current reformer and supporting capacity (e.g., hydrocracker capacity) is adequate, and increased severity of operation (of the naphtha reformers) and increased use of existing alkylation capacity will permit Canada's refiners to meet the new requirement at minimum added capital cost without major recourse to oxygenated octane boosters.

4/ Phase-down with increased severity operation will lead to a modest 0.8% or so increase in crude oil consumption, compared to operations at the 1984/1985 average of 0.49 g of lead/L.

5/ Substantial new investment will be required to meet the longer range phaseout goal. Energy and crude oil consumption in refineries will increase by 2% or so compared with that needed at the 1985 lead use level if only process changes are to be used as a route to the required higher clear octane requirement.

6/ The Canadian requirement for new equipment and increased oil consumption to meet the phaseout goal will be reduced if substantial proportions of synthetic crude and cracked heavy oil are used as feedstocks.

7/ The increased requirement of crude oil to meet the phaseout goal can be eliminated and further volumes of crude oil backed out by the incorporation of oxygenates in the blending of gasolines (leaded and/-or unleaded grades). The requirement for capital investment in the refinery will be reduced, but new investments would be required in plants to meet an expanded requirement for alcohols or MTBE.

8/ The use of oxygenates in gasolines is widely practiced outside Canada. Gasohol (ethanol 10%, gasoline 90%), methanol-co-solvent gasoline blends, and MTBE are the preferred materials. Unlike tetraethyl lead, which is a catalyst used in small volume in gasoline, the use of oxygenates requires robust volumes in the region of 9 to 12% by volume of gasoline to be effective. This is in line with the refiners' experience with alkylate, toluene, and other high-octane refinery streams. The oxygenates are, therefore, gasoline extenders and must compete on a cost basis with refinery streams and high severity processing.

9/ With the exception of Mohawk Oil, which markets small volumes of blends of methanol and subsidized ethanol in gasoline in the four western provinces, and a demonstration in the Toronto area (managed by Sun Oil Co.) of a blend of methanol, isobutanol and gasoline (9.5% alcohols by volume termed "V-Plus" by the marketer Alberta Gas Chemicals, a division of Nova Corp.), Canadian refiners have not yet included the use of oxygenates in their plans to meet the 1987 lead level. It is uncertain whether they will adopt alcohol addition as a route to the no-lead requirement, but many are ready to follow the US and European practice involving the addition of gasoline-compatible MTBE when their supply of octane becomes tight.

The LPG, and especially the butane balance in Canada's refineries, will be affected by the adoption of oxygenated gasoline blends. Therefore, an attempt is made to quantify the effect of lead phaseout and the use of three candidate oxygenated materials in the production of a fixed slate of petroleum products manufactured to current specifications, using a computer model to simulate the operations of an Ontario refinery of known coneiguration. The details of the analysis follow.

The refinery was configured to produce 30 000 BPD of regular gasoline as either all unleaded or as unleaded and leaded (to the 1987 0.29 g/L lead specification) in equal volumes. The refinery produced the same volume and range of products as now provided to the market (gasolines for automotive and aviation purposes; Jet A and Jet B turbo fuels for aircraft; diesel fuels; light fuel oil and stove oil; heavy fuel oil and specialty

products).

The refinery was assumed to operate at up to 99 research octane number (RON) severity in the naphtha reformer, to produce alkylate from all propylene and butylenes produced using isobutane as the co-reactant, and to use a C5-C6 isomerization unit to assist in meeting the required octane specification for gasolines. The volume of oxygenate added corresponded to the tentative specification such that the oxygen content of gasoline did not exceed 3.7%. Summer and winter vapour pressure requirements were met by adjusting the components used in blending the gasoline, with n-butane used to bring the vapour pressure to the legislated seasonal limit to provide front-end volatility for winter driving and to reduce vapour lock problems in summer. The principal consideration in the analysis was to determine the volume of butanes and propane backed out by the use of oxygenates or produced by high-severity operations. A secondary purpose was to determine which of the oxygenates could compete on a cost basis with the standard no-oxygenate options.

The outcome of the analysis is summarized in Table 8 and the following:

Crude Oil Savings

The elimination of lead in the production of gasoline is likely to increase crude oil use by 2% beyond the 1984 (0.49 g/L lead) levels and 1% beyond the 1987 (0.29 g/L) level without the use of oxygenates. The use of oxygenates in both leaded and unleaded grades can lead to reductions in crude oil requirement greater than the volume of oxygenate added.

In the case of MTBE addition to both grades at the level of 10%, 1 volume of MTBE can generate 1.25 volumes of oil displacement, but the methanol blends can only generate 0.8 volumes of crude oil saving for each volume of oxygenate used. The restriction of oxygenates to use when no-lead grade is produced reduces the value of oxygenate additions in terms of oil displacement.

Propane Production

The phaseout of lead from the 1987, 0.29 g/L level requires higher severity operations in the refinery and leads to increased oil consumption in all cases. The higher crude requirement in each case leads to an increased production of exportable propane. An increase of up to 11% is noted when lead is phased out without oxygenates being used. The addition of oxygenates does not greatly affect the yield of propane in the unleaded cases but reduces the propane yield in all cases where blending with lead is continued. In the case of MTBE addition at the 10% level and when lead is still permitted in 50% of the gasoline marketed,

propane production will be reduced by about 27% compared to the situation without oxygenates.

Butanes Balance: Isobutane

In all cases with and without oxygenates, with and without lead there will be a continued demand for i-butane imports. There is no significant change in the volume of i-butane required between cases where lead blending is continued in 50% of the gasoline marketed, but there are substantial differences in i-butane requirements when crude oil volumes are reduced by the addition of oxygenates to the gasoline blends. The addition of MTBE (10% by volume), for example, causes an 18% reduction in the demand for i-butane, whereas the addition of (9.5% by volume of) the methanol blends causes a 9% drop in the i-butane requirement.

Butanes Balance: Normal Butane

The demand for n-butane in the refinery examples varies widely with process conditions and the oxygenate used. All oxygenated blends (with the exception of MTBE used where lead is retained) have a reduced need for n-butane. Imports of n-butane into the refinery are eliminated, and surplus refinery n-butane is available for export from the refinery. The surplus of n-butane is highest where lead is not permitted and high-severity reforming operations are involved. The n-butane displacement ("butane back-out") is greatest for the Oxinol blends, where n-butane must be disposed of at up to 1.8% of the volume of crude oil processed where no lead is permitted, but only at 0.6% of the volume of crude oil processed when lead is permitted. MTBE with lead blending permitted is exceptional in permitting an increase in the use of n-butane to 1.4% of the crude oil processed, compared to 0.9% in the base case (no oxygenates used, lead blending permitted for 50% of the gasoline sold). A similar increase in the volume of n-butane that can be blended into gasolines was noted when n-butanol was used as the oxygenate).

The total butane (i- and n-) back-out amounts to about 2% of the crude run with methanol-butanol blends where lead is not permitted, to the 1.5 to 1.6% of crude level when lead blending is permitted.

With MTBE used, where lead blending continues in half the gasoline at the 1987 legislated level, there is no change in the total butane requirement compared to the base case but a sharp reduction when lead is phased out: this is evident only in the n-butane component.

Butane Requirements of Oxygenates

Although n-butane may be backed out in refineries using purchased oxygenates, the total Canadian demand for butanes will not be reduced. The oxygenate most favoured by refiners is MTBE; methanol co-solvent blends

rank a distant second position.

MTBE production requires a source of isobutylene and methanol, and the refinery isobutylene stream may be diverted from the production of alkylate to MTBE production. However, this would reduce the volume of alkylate produced and the total level of the octane enhancement available to the refinery. Large-scale adoption of MTBE will therefore involve the production of isobutylene from i-butane (by dehydrogenation) with the i-butane itself generated from n-butane by isomerization. About 0.95 volumes of butanes are required for each volume of MTBE produced. A large increase in the requirement for butanes may therefore be created where MTBE is used as the oxygenate. (The increase is all the greater, since MTBE can be used with little or no butane back-out in the gasoline blending step).

ARCO chemicals in the US has established a market for Oxinol, a 1:1 mix of t-butanol and methanol. The company has resolved distribution, storage, and vehicle use problems, and Oxinol may be considered a commercial product that may be used at the maximum 9.5% by volume level in the production of specification-grade leaded and unleaded gasoline. The maximum 9.5% by volume level is determined by the requirement (developing CGSB specification) that the oxygen content of gasoline not exceed 3.7%. Furthermore, the US automobile companies state that fuels containing more than 5% methanol should not be used in current vehicles. In practice, the blending of t-butyl alcohol reduces the vapour pressure of the gasoline to specification levels and overcomes the problem of phase separation into a gasoline-rich and a methanol-rich layer which occurs without the higher alcohol co-solvent.

The t-butanol required can be manufactured from either isobutane or isobutylene and, as with MTBE, creates a new requirement for "butanes" far in excess of the volumes that must be withdrawn from gasoline blending for vapour pressure control.

As shown in Table 9, the production of the oxygenated gasolines and other products using MTBE or Oxinol technology requires butanes import of between 3.4 and 11.5% of the volume of crude oil processed. This is a significant increase over the 3.6 to 2.7% level required for the production of the gasolines and other products without these oxygenates.

Other oxygenates have been investigated. The isobutanol required to formulate V-Plus gasoline can be produced from propylene but not in the volumes required by the refining industry, without depleting the propylene needed in refineries for alkylate and polymer gasoline production or installation of new facilities to dehydrogenate propane.

Similar considerations apply to the production of isopropyl alcohol, a high vapour pressure component, which may also be used to formulate oxygenated gasolines with and without methanol addition. Ethanol may be used as an oxygenate-gasoline extender with and without methanol. Alcohols lower than butanol, which have high blending vapour pressures, water sensitivity problems, and high butane back-out ratios, are uneconomic in comparison with MTBE and methanol-butanol blends. They are likely to be used without subsidies only occasionally, at locations where surplus alcohol production exists, for example, at integrated petrochemical/refinery complexes.

One interesting new technology which eventually may influence oxygenate blending is the co-production of higher alcohols with methanol, using catalyst and process modifications in an otherwise standard methanol-from-natural-gas plant. Conditions have been found that produce a mixture of methanol (80% by volume), ethanol (3%), n-propanol (5%), and isobutanol (12%), known as "methyl fuel," which reduces butane displacement compared to methanol by 15% or so. However, the product is not commercially available, and the process is expensive to operate.

6.5/ Syncrudes to Refineries

The National Energy Board (NEB) had suggested in 1984 that 68 500 m^3/day of new syncrude capacity would be operational by the year 2000, from expansion of the Syncrude plant, the construction of two new medium-scale plants, and introduction of a series of in situ bitumen production and heavy-oil upgraders. The effect of the heavily processed syncrudes on the LPG balance is illustrated in Table 10. The addition of 68 500 m^3/day of syncrude would generate 8500 m^3/day or so of LPG, that is, about 8000 m^3/day more LPG than would be generated on a net basis by refineries fed conventional crudes. The major product would be n-butane (7000 m^3/day). The distribution of the new volumes of syncrude to a number of refineries for processing with conventional crudes would have the same overall effect on LPG production.

6.6/ Assessment of Factors Affecting the Future Butane Balance in Canada's Refineries

It appears from interviews with vehicle producers and refiners that the specifications for gasoline will not be greatly changed in the future, except perhaps for a modest increase in the RVP made in response to the alcohol-in-gasoline industry. An increase in the maximum RVP of gasoline by 0.5 psi (3.4 kPa) is anticipated for both oxygenated and conventional gasolines (this despite US consideration of reduced RVP levels to minimize evaporative emissions): the increased RVP would enable more butane

to be blended into conventional gasoline. The use of the manganese octane improver methylcyclopentadienyl manganese tricarbonyl (MMT) in leaded and unleaded grades is expected to continue despite prohibition of its use in US unleaded grades.

The Canadian refiners plan not to use alcohols to achieve the octane requirements of unleaded gasolines; they much prefer to use refinery changes, with MTBE being used where required (the principal reasons being the compatibility of MTBE at all blending levels needed with gasoline, the fuel distribution system, and the economy achieved through maintenance of the use of large volumes of n-butane to formulate gasolines). Local use of blends may occur, particularly where provincial tax concessions may be available for the oxygenated fuel, the principal fuel in this category being gasohol or gasoline blended with methanol (5%) and ethanol (3%). Even more limited use is expected in the future of other methanol-co-solvent blends, growth of which is dependent upon substantial price reductions and increased availability of higher alcohols, such as the butanols or isopropyl alcohol. It is anticipated that a plant to manufacture MTBE will be constructed in Canada by the early 1990s, which will maintain or increase butane use in gasoline, offsetting the small increase in butane availability from processing of heavier crudes and reduced demand for butanes in refineries processing increased volumes of syncrude or formulating alcohol-containing gasolines. See Table 11.

In view of the continued demand for butane for gasoline production, it appears that the price of butane relative to gasoline and crude oil will be maintained (or increased) in the future and that large surplus supplies of low-cost butane will not be available for augmentation of propane supplies. The supply/demand and price relationship between butane and propane is further examined in the next sections.

7/ THE SUPPLY/DEMAND BALANCE FOR BUTANE AND PROPANE

7.1/ The Factors Affecting Butane Demand

The principal reason for the present investigation is the concern that the future development of propane carburetion will be limited by propane supply and the potential for augmentation of the propane supply by butane, the demand for which could be reduced if major volumes of alcohols were used to produce future gasolines. Section 6 has provided evidence that the demand for butane for gasoline production is unlikely to be reduced, since the demand for butane for blending into gasoline will not be substantially reduced. If, as anticipated, refiners choose MTBE as the oxygenated octane booster and if MTBE or methanol/co-solvents were to be adopted as octane boosters, the demand for butane for the production of MTBE or butyl alcohols would increase the total demand for butane. The possibility that large new volumes of butane would be available from high-severity refinery operations and that methyl or ethyl alcohol (without co-solvent butanols) would be used is considered unlikely in view of the adverse economic effect of butane back-out and the high cost of ethanol.

The changes that may take place in the refinery to meet lead phase-down and eventual phase-out will increase the volume of refinery propane production more than the volume of butane, and the incentive to blend butane into propane to augment propane supplies from refineries is unlikely to arise. However, the demand for propane and butane for other than automotive fuel use will also affect the supply/demand and competitive price of butane and propane versus gasoline. A summary of the factors affecting these markets is examined next.

7.2/ Markets for Butane

7.2.1/ Refinery Use of Butane

The use of high-octane, low-cost, n-butane as a blending agent is the major outlet for n-butane. The major outlet for isobutane is in the in-refinery production of alkylate (using butylenes and propylene). As noted previously, refinery use of butanes is not expected to decrease substantially, even with the withdrawal of leaded grades of gasoline, since the most practical alternative for refiners to meet octane needs involves high-severity reforming (and other refinery processes such as hydrocracking) with increased production of alkylate augmented by the addition of MTBE (and, perhaps, butanol-containing methanol blends).

The refiners have two options for their procurement of MTBE. Some refiners may elect to convert the isobutylene in the fluid catalytic cracker (FCC) streams to MTBE using purchased methanol (with continued use of their alkylation units to convert other butylenes in the FCC stream to alkylate); others may purchase MTBE from US producers and, when available later, from a Canadian plant.

7.2.2/ Chemical Use of Butane

The use of butane as a chemical feedstock is currently limited to its oxidation to acetic acid (Celanese Chemical in Alberta) and other quantities used in the Sarnia area and in Montreal as feedstock for ethylene production. In 1985, these petrochemical uses required a total of 343 800 m^3 of butane (940 m^3/day or 5900 BPD or 17% of Canadian use and 7.7% of Canadian production of butanes).

There are two major new outlets for butanes in the future. There are plans to increase the use of butanes in the production of ethylene through changes in the Petrosar (Sarnia) and Petromont (Montreal) ethylene crackers to reduce their dependence on naphtha. But with current naphtha prices there may be a delay in the buildup of butane demand previously projected by NEB and others.

The effect of low crude oil prices will similarly delay plans for the production of MTBE in Canada, despite the availability of methanol and surplus capacity for the production of i-butane (the precursor of isobutylene in a new world-scale MTBE plant) in Sarnia and Edmonton. Nonetheless, within the period to 1995 it is expected that the conversions of ethylene crackers or a world-scale MTBE plant will be in operation, creating a new demand for butanes.

7.2.3/ Solvent Flood Use of Butane

Butane is a component of the natural gas liquids currently used for the solvent flood recovery of crude oil in Alberta. NEB and the natural gas liquids (NGL) plant operators anticipate that the use of NGL in solvent flood oil recovery will decline after reaching a peak in 1990. Secondary oil recovery projects using NGL as solvent may thereafter become a source rather than a sink for butane, propane, and other NGLs. Continued availability of low-cost foreign crude oil may accelerate the decline in NGL use for secondary recovery, since the solvent flood method is a costly means of oil recovery. Commitments to operate NGL plants and solvent recovery operations are long term and are expected to continue at a slower rate with reduced value NGLs.

7.2.4/ Exports of Butane

The US refiners are a major market for Canadian butane. In 1985 some 2.5 million m^3 (6750 m^3/day or 42 600 BPD amounting to 54% of Canadian production) were exported at an export realization of $375 million. The high volume of exports provides a large buffer stock available to meet an expanded use of butane in Canada.

7.3/ Butane Supply/Demand

The many factors that affect butane demand for the domestic and export markets make projections of the supply/demand balance risky. Our estimate of the balance derived from NEB, industry, and our own data is illustrated in Figure 5.

The forecast is that butanes available beyond the requirements of conventional and expanded petrochemical demand in Canada will shrink from about 54% of the total 1985 production of 12 500 m^3/day to 25 to 37% of the volume available (12 000 m^3/day) in the year 2005. That is to say no increase in the current 6750 m^3 surplus is anticipated; exports may need to be reduced to the 3000 to 4500 m^3/day level to meet the increased demand for butane in petrochemical applications.

7.4/ Propane Supply/Demand

The use of propane in Canada is anticipated to increase by about 13% from current levels to a 1990 peak consumption at about 12 500 m^3/day only and to remain static or decline slightly thereafter. As shown in Figure 6, a decline is expected in the use of propane for solvent flood, offset by increases in propane use for transportation, industrial heating, and petrochemicals. The level of propane production is expected to increase at a greater rate than demand, with the result that by 1990 the surplus available for exports will be at 42% of production and by 1995 at an even higher level, 47 to 51%. Even at a pessimistic production level of 20 000 m^3/day for year 2005, the surplus available for export is estimated at 40% of the Canadian supply. Propane industry estimates of the surplus in 2005 are even higher, at 50% of Canadian supply. At the current propane consumption level (which may decrease as vehicles become more fuel efficient), the lower estimate of 1995 surplus supply would be sufficient to power 945 000 propane vehicles, some 750% of the current propane vehicle population in Canada and 400% of the 235 000 vehicles forecast to be operating in 1995.

Even by year 2005, under the most adverse propane supply conditions, the surplus is expected to be sufficient for the addition of 685 000 propane vehicles to the optimistic forecast of 305 000 propane vehicles in use.

With competition in part of the propane vehicle market coming from compressed natural gas, it appears that a 305 000 propane vehicle level may be difficult to achieve by 2000 to 2005 and that automotive propane fuel availability will not need to be augmented by butane.

7.5/ Conclusions on Supply/Demand

The Canadian demand for propane and butane appears to be substantially less than the supplies available through the period to 2005. A large increase in the production of butane may be encountered in the period beyond 1992/1993 if refiners choose to solve their lead phaseout octane shortage problem solely by changes in the refinery processes. This will be favoured if oil prices remain at distressed levels. It is more likely that refiners will utilize MTBE (or equivalent methanol-butanol mixes) as an adjunct to refinery changes and that the net demand for butane will not be reduced significantly if the butane requirement of the oxygenated octane improvers is included.

An increase in the severity of refining operations will produce more propane in addition to butane. The propane will need to be cleared and the automotive demand for propane represents a high-value use for the added propane. Butane has attractive uses outside the automotive LPG market.

The demand for propane, butane, and LPG mixes in conventional and automotive use will be greatly determined by the relative price of the commodities. This is examined in Section 8.

8/ THE RELATIVE PRICE OF PROPANE, BUTANE, AND PETROLEUM PRODUCTS

8.1/ Historic Price Relationships

In comparing the price and value of propane, butane, crude oil, and petroleum products it is important to note that the very different densities of the liquids complicate the price comparisons.

The historic relationships on a volumetric cost basis between crude oil, butane, and propane are illustrated in Figure 7. This shows that, since 1976/1977, butane prices FOB Alberta gas separation plants have varied from 140% of the price of propane (March 1986) to 185% in 1982. A similar premium was realized for butane export sales. Both propane and butane are marketed at a discount to light crude oil on a volumetric basis. The magnitude of the discount varies by location (due to transport charges), as shown in Table 12. Thus, in 1976 to 1985 the price of butanes in Alberta was about 80% of the price of crude oil on a volumetric basis, and the price of propane, about 57% that of crude oil on the same volumetric basis. On an energy or weight basis, butane has enjoyed a premium over crude oil (since a volume of butane contains only 74.3 to 74.5% of the energy content of a type light-to-medium gravity crude oil). However, when refinery costs are added, the prices of premium refined petroleum products (gasoline, diesel, and light fuel oil) are substantially higher than those of butane and propane on a volumetric and energy basis. This is because refinery costs and losses are encountered in processing crude oil to useful products, but propane and butane require no processing beyond the separation plants in Alberta or Sarnia. These cost relationships account for the interest of refiners in retaining the maximum of n-butane as a gasoline blending agent (where butane cost on a volume basis is low) and of isobutane as a feedstock for alkylate production. Historically, isobutane commodity values have been 1.0 to 1.5¢/L higher than n-butane values, since isobutane allows low-cost refinery propylene and butylenes to be converted to the high-octane gasoline component alkylate.

In addition to its premium value compared to propane in gasoline production, butane has a higher value than propane as a feedstock for ethylene production, where propane or butane may be used as substitutes for naphtha when ethane is not available. N-butane in this application is valued in commodity markets at 106 to 110% of propane on a weight basis or at 118 to 125% on a volumetric basis.

The commodity value of propane in Canada is predominantly determined by competition with number 2 fuel oil (and natural gas, where available), where butane is not applicable (due to a low-temperature storage

problem). In international markets, propane commodity values are also determined by naphtha values and butane values.

The retail market and fleet price of automotive propane and automotive butane (in a new grade of LPG) is complicated by federal taxes (excise tax on gasoline and sales taxes on gasoline and propane) and provincial road fuel taxes, which vary by province and fuel (automotive propane being taxed only in Manitoba, Quebec, and Atlantic Canada; gasoline being taxed at the provincial level in every province but Alberta and Saskatchewan).

8.2/ Future Price Relationships

The prices of butane and propane are adjusting to the March 1986 collapse in the world price of crude oil and are expected to return close to historic relationships with crude oil noted previously. Until 1987 automotive propane will enjoy a large tax advantage over gasoline through forgiveness of the excise tax on propane. Gasoline is taxed at 3.5¢/L for personal use and 2¢/L for commercial and farm use, which is scheduled to be increased to 4.5 and 3¢/L on January 1, 1987. Another advantage of propane use is the federal sales tax on automotive propane, which was set at 17% of the 12% sales tax (scheduled to increase to 13% in 1987), because the road fuel sales tax was distributed over all propane sold, including propane for non-automotive uses.

Gasoline carries the full sales tax. The federal sales and excise tax remissions for propane in 1987, therefore, total about 4.85¢/L of gasoline equivalent for personal users and 3.35¢/L gasoline equivalent for commercial and farm vehicles. In addition, B.C. and Ontario exempt propane but not gasoline from the provincial road tax (about 9.25¢/L and 8.3¢/L advantage for propane), and favourable treatment is afforded automotive propane in Manitoba, Quebec, and B.C. It is uncertain how long the favourable tax treatment for propane will continue and what the tax reaction to the butane content of an LPG might be. It is of interest to note the following:

- Manitoba introduced a tax on natural gas in May 1986 (the first instance of NGV tax in Canada) and increased the tax on propane at that time.

- Ontario limited the sales tax remission for propane vehicles to $750 in May 1986, whereas before then the full 7% sales tax was remitted on propane vehicles.

- The federal government's taxable propane conversion grant of $400 was terminated 31 March 1985 and has not been replaced.

- The addition of butane to gasoline provides a substantial portion of the federal gasoline excise and sales tax revenue and provincial fuel tax revenues: the use of the same butane as an extender of propane to displace gasoline sales with loss of revenues presents a more difficult argument for the retention of favourable tax treatment than for propane which has no corresponding "transfer capability."

8.3/ Some Conclusions from Price Considerations

1/ Butane and isobutane have high values as gasoline extenders and octane improvers, these values exceeding that of butane used as an extender of propane in a new grade of automotive LPG. (Propane cannot be used to extend gasoline in this direct blending way).

2/ An alternative use of butane is to increase the volume and octane value of gasoline through production of alkylate (isobutane) or MTBE (from either butane or isobutane).

3/ In circumstances where increased supplies of both propane and butane become available, butane may be expected to displace propane as a petrochemical feedstock (in US plants served by Canadian exports and in Canadian plants when ethane capacity is fully utilized or MTBE is produced).

4/ Because of cost differential and low-temperature storage and use capability, propane will maintain its dominance in heating fuel markets. The low-temperature performance determines the value of automotive LPG blends.

5/ The high netback on butane used in gasoline limits the market for alcohols as gasoline extenders and the volume of butane that could theoretically be displaced by the use of alcohols in gasoline.

6/ Should certain refineries elect to meet the future octane shortage by increased severity of refinery processing, added volumes of both butane and propane will be produced. The added propane volumes will need to be cleared, and no cost advantage will be available from the switch to a butane or a propane-butane automotive fuel. The added propane volumes will delay the need for introduction of a butane-containing automotive LPG.

7/ The historic higher value associated with butane is likely to continue in the future, and demonstrations of some performance advantage for a butane-containing LPG may be necessary to justify its use as a propane extender or substitute.

9/ PROPANE-BUTANE BLENDS EXPERIENCE AND PROPERTIES

9.1/ Blend Technology Requirement

The 1984 report by Chrysler Canada provides an overview of the properties of propane-butane blends and certain European and US experience in their use. This section provides further detail which demonstrates that propane-butane blends can be used effectively in spark-ignition engines where supply considerations dictate use of blends.

In Canada, where high-octane propane is widely available, the development of technology compatible with propane-butane blends is, at best, of long-term interest. However, the development of engine designs that are compatible with blends and with dual-fuel operation is essential if propane vehicles and conversion equipment of Canadian manufacture are to be exported.

9.2/ Experience Outside Canada

The use of LPG as an automotive fuel originated in the southern US and was further developed from the 1950s in Italy and the Netherlands in response to local surplus supplies of gas-sourced product (US south) and refinery product (Europe). The composition of LPG for automotive use varies widely from country to country and from season to season. The Canadian standard defining the motor octane number and the hydrocarbon composition limits, which determine the octane number of automotive Grade 1 propane (HD-5 in this report) fuel specified in the Canadian standard CAN 2-3.14-M78, is of recent origin. This standard cannot be applied in Europe due to the lack of fractionation facilities and vehicle designs which do not require HD-5. The European Committee on Alternative Fuels has set the task of "harmonization of LPG composition" in Europe as the most important target for European joint legislation and the development of a system "that detects the composition of LPG and automatically corrects the (in-vehicle) LPG system" as the most important research and development task.

The wide variation in LPG composition measured by the propane and butane composition limits (Table 13) reflects:

- the need to market both propane and butane in Europe (principally LPG from refineries);
- the high level of propane required for winter volatility purposes in the cold countries (Canada, Sweden, and W. Germany) and the high tolerance of butane in warmer climates (Italy and Spain); and
- the problems that will be encountered with variation in fuel composition in moving from one country to another.

The problem of varying automotive LPG composition has confined vehicle conversions in Europe to post-purchase installation of dual-fuel systems, where the fuel octane requirement of the engine is determined by gasoline and can readily be met by refinery LPG, which may contain propylene, butane, and higher hydrocarbons in addition to propane. However, in France to 1984 only mono-fuel LPG systems were permitted. In the Netherlands and Canada, mono-fuel buses are in operation. In Italy and Spain, automotive LPG is essentially butane.

This commercial experience in variable automotive LPG composition, reports of the European LPG R&D committee and literature on storage, and transport and engine tests of various LPG compositions have been used to generate the following assessment of the problems and opportunities associated with use of blends in Canada.

9.3/ Automotive LPG Cost and Supply

Canadian refiners value butanes, propylene, and butylenes for the production of gasoline, alkylate, and polymer gasoline. The lowest period of refinery demand for n-butane is in the period March to June, when summer grades of gasoline are being produced. The seasonal variation in demand for n-butane means that this product could be available to augment automotive propane on a seasonal basis. In summer ambient temperatures would permit use of butane in propane without exaggerating the winter cold-start problem of post-purchase propane conversions. This would be acceptable provided the summer LPG-grade was cleared in the summer and not supplied in winter.

The disposition of n-butane to automotive LPG in the summer would reduce the need for storage somewhat, but very large storage facilities already exist for butane and mixed LPG to serve the needs of the gas liquids industry (about 1.3 million m^3 of butanes and 1 million m^3 of LPG storage is available in Canada in addition to the 2.7 million m^3 storage available for propane). The Sarnia fractionation facility of Dome/Amoco is the major user of mixed LPG storage, since the facility receives mixed LPG in batches from Alberta via the Interprovincial Pipe Line (IPPL) pipeline. The LPG received at Sarnia must be separated from the crude oil or diesel buffers used in the pipeline, and the cost savings from use of a mixed butane-propane automotive grade would likely arise only from energy (natural gas) cost savings in the fractionator in the order of 0.05¢/L for a product with 10% butane and RVP of 175.5 psia (1210 kPa), compared to the HD-5 standard of 2.5% butane (with a RVP of 188 psia [1296 kPa]) whereby a 14% saving in the depropanizer energy cost would be achieved. Similar savings in refineries would be eligible in relation to the crude oil cost and total cost of refinery propane.

The conclusion on butane-containing blends is that these could be made available on a seasonal basis but that savings in fractionation costs would not be a significant factor.

9.4/ Local Storage, Transport, and Distribution Costs

The seasonal availability of a butane-containing LPG would require or result in the following:

- Segregated storage at the producing location for the new specification product would be needed because it would not be co-mingled with the HD-5 grade or specification butane.

- Transport costs must not increase, since specification product is essentially transported already by rail and road tanker to compete with pipeline transport of LPG, fractionation and local distribution;

- Steps would need to be taken by local distributors to remove the new mixed LPG product from tanks that will serve HD-5 grade in winter. Some duplication of local storage bullets is likely, as is contamination and off-season misfuelling (misfuelling could have negative sales effects if cold-start experience deteriorates further).

- The increased hazard associated with the bulk handling of butane-rich LPG must be considered. The lower explosive limit for butane is 1.85% by volume in air versus 2.37% for propane, and butane has a higher density than propane and may "puddle" more and evaporate/diffuse slower on spilling than propane. This is a matter of degree and dependent upon the volume of butane in the LPG mix. The acceptable level adopted for tank car emissions of butane-rich LPG, for example, is more stringent than for propane

- Loss of potential revenue from the sale of high-energy-density butane at propane prices would occur unless means were developed to correct metering devices for butane content in propane, which is sold for automotive use by the litre.

In perspective, there will be certain additional expenses to handle both grades of LPG, which will be a nuisance and expense to distributors to the extent a discount price to distributors would be necessary to ensure their acceptance of the new grade and investment is needed to avoid misfuelling problems. The problem is compounded by the large number of small-volume automotive distributors existing in Canada. (According to a recent survey by the R.F. Webb Corporation, the average retail pump sales in 1985 were only 3040 L of propane per station per month).

A major disadvantage of butane-containing LPG will be the effect it may have on the parking of LPG vehicles in garages and underground. The increased density of the vapour, increased time to disperse spills, the lower explosion limit, lower ignition temperature, and higher rate of flame propagation (Table 14) all make butane somewhat less satisfactory than propane: butane-containing LPG will have an intermediate safety rating.

These same concerns for butane blends could have an adverse impact on the introduction of self-service public refuelling stations, which is a necessary condition for widespread use of propane in automobiles. More attention is needed to be given to the location of bulk LPG storage tanks to improve fuel spill disposal and prevent LPG vapour accumulation in gullies, pits, and other depressions. (Further detail is provided in "A Safety Manual for Propane Bus Systems," Transport Canada, Report TP-5493E, 1984.)

A safety problem associated with variations in the composition of automotive LPG has been reported in Europe. Vehicles previously filled with propane may have an internal tank pressure too high to be filled by a mixture of propane and butane, unless an ullage or "spitter" valve is incorporated in the tank, which itself is a source of fuel spillage and fire hazard. The issue of fuel tank overfilling beyond the 80% tank volume level described in the safety legislation is not significantly affected by substitution of part of the propane by butane, but at bulk storage sites an additional volume of LPG can be stored, since the vapour space or ullage required by regulations is related to the vapour pressure of the LPG stored at a given temperature.

9.5/ Vehicle Performance Changes with an LPG Fuel

9.5.1/ Current User Views

A recent survey (R.F. Webb Corporation Limited, et al, "Evaluation Study of the Propane Vehicle Grant Program, Energy, Mines and Resources Canada, August 1986) showed that 80% of propane vehicles operated on highways in Canada were post-purchase conversions and 90% were mono-fuel vehicles (only 3% of commercial vehicles were dual-fuel). Although over 90% of those who had received federal grants toward the cost of conversion had achieved or bettered their pay-back expectations on the net conversion investment, only 35% were convinced that they would continue to use propane, and about the same number were undecided. There is clearly a substantial dissatisfaction with the technical performance of propane vehicles and conversion services. Table 15 lists the problems reported.

It is important to bear these current fleet composition and conversions in mind when considering change in the fuel composition, since, in the future as in the past, the majority of propane vehicles will be post-purchase conversions regulated by provincial legislation and not "propane-designed" vehicles purchased directly from the manufacturer, who must comply with the Canadian Federal Motor Vehicle Safety Standard (MVSS) 301.1. However, neither provincial nor federal regulations on propane vehicles address the relative performance of the vehicles, except with respect to safety.

9.5.2/ Low-Temperature Performance

As shown in Table 15, cold start in winter is the most frequently encountered problem with propane vehicles, and any change in the fuel composition must not increase the frequency of the problem. Propane-fuelled vehicles have no fuel pump and depend upon tank vapour pressure to feed liquid propane to the vaporizer. Automotive propane contains small quantities of high-vapour-pressure ethane and may contain propylene, which provide a small residual vapour pressure when propane itself, at -40°C or so, has none. Longtime (10 h or so) storage of propane vehicles at ambient temperatures of -40°C or thereabouts will reduce the vapour pressure to the point where insufficient vapour pressure exists to pump fuel and the vehicle and fuel must be warmed to permit start-up. Currently automotive propane is not formulated to avoid this winter cold-start problem, which is most prevalent in areas where regulations prohibit the storage of propane vehicles inside a garage building.

A further cold-start problem arises when there is insufficient heat transfer in the vaporizer to maintain propane vapour supply to the engine, even when the vaporizer has sufficient liquid propane. The use of butane, which has a boiling point close to 0°C (-0.5°C), in an LPG will reduce the vapour pressure to the point where fuel may not be pumped to the vaporizer in winter, or if pumped, may not vaporize after start-up and may even pass through the vaporizer as liquid when an excessively rich mixture would be delivered to the carburetor.

While use of a block heater or operation of a dual-fuel engine on gasoline to warm up the system before switching to propane avoids some of the problems of winter cold start, many carburetion system designs are clearly inadequate for winter service in Canada. Most kit manufacture occurs in Italy, California, and the Netherlands, where Canadian winter conditions are not considered or understood. Because many current designs are unsatisfactory below -10°C, even with HD-5 grade propane, the use of butane in an LPG mix must be strictly limited in Canada to summer use, in spite of the theoretical argument that even at -20°C or so a 50% butane/

50% propane blend has a vapour pressure of 80 to 85 kPa -- sufficient to pump the fuel and avoid carburetor flooding with liquid fuel.

The use of fuel blanket heaters in addition to block heaters and dual-fuel engines could permit the introduction of a new grade of automotive fuel for use year-round, but only at the expense of low fuel economy inherent in dual-fuel designs.

A potential solution to the winter vapour pressure limitation that has been suggested is to spike the LPG blend with sufficient ethane to overcome the vapour pressure loss incurred through butane addition. In practice, the very high vapour pressure of ethane and the low octane value of butane relative to propane restrict the quantity of both ethane and butane that can be added. A typical HD-5 propane is close to the legal vapour pressure limit (200 psig and 100°F), and such compositions may frequently contain up to 1.5% by volume of ethane along with the 2.5% by volume maximum of butane allowed in the specification. No change in the vapour pressure regulation to provide a "winter-grade" option is recommended for safety reasons.

Other solutions to the cold-start problem will be available from current work on propane fuel injection systems. A Daimler-Benz development uses a new vaporizer for propane or methanol, and a vapour injection system. Others are investigating direct propane injection.

9.5.3/ Olefin Content

The HD-5 specification limits the level of propylene to 5%. The limit restricts the degradation of the octane rating of the fuel. In engines with high fuel throughput (city buses and trucks), propylene also manifests itself as an oily or waxy propylene polymer, which accumulates in the vaporizer.

It will be important to place even more stringent limits on the level of butylenes that may accompany butane in an automotive LPG, since butylenes polymerize even more readily than propylene.

9.5.4/ Octane Rating

In dual-fuel vehicles the compression ratio, and, hence, efficiency of the engine, is limited by the octane rating of gasoline and the need to provide a margin in octane rating (octane requirement increase) to overcome the effective increase in compression ratio and preignition knock due to the accumulation of deposits in the cylinder over time.

The octane rating for the LPG used in dual-fuel engines is therefore not critical. This permits use of high butane content LPG such as that used in Italy.

With propane-dedicated vehicles, on the other hand, strict control of the octane rating of the fuel can pay dividends if the compression ratio of the engine can be increased, since that leads to a higher thermal efficiency in the combustion process. The motor octane number (MON) of the fuel is the more important measurement for propane engines.

The octane ratings of gaseous fuels, the critical compression ratios, and thermal efficiencies available are illustrated in Figures 8 and 9 for a typical single cylinder test engine, the Co-operative Fuel Research (CFR) engine. In practice, compression ratios and fuel efficiency must be reduced to more modest levels than those indicated by research engines. Chrysler, for example, has adopted a 9.2:1 compression ratio for its propane engines, compatible with the 95 MON rating of HD-5 propane and optimization of the spark timing, which is possible in a factory-produced propane engine. After-market conversions do not increase the compression ratio and may not optimize spark timing: rules of thumb for spark timing are frequently adopted in conversion shops. These factors affect the fuel economy of propane conversions, but the low compression ratio, coupled with the use of a 95 MON fuel, overcomes the deficiencies in spark timing.

While engine damage due to knock is not frequently reported as a problem with conversions, it is apparent from the survey of propane grantees that a high proportion of after-market conversions give marginal performance and fuel economy ratings. A frequent source of problems is failure to block off the heat supply to the air fuel intake, which is necessary to vaporize gasoline but which leads to power loss and, in extreme circumstances, to engine knock with propane. (Dual-fuel engines retain the manifold heating and, accordingly, suffer power loss from this cause but do not knock, since the compression ratio is low). The introduction of a high-butane-content LPG for summer use would expose the engine to the least knock-resistant fuel in the period of highest ambient temperatures.

Many tests have been reported (see Section 12) which indicate that propane vehicles can be operated without problems on mixtures of propane with butane, propylene, and other low-octane hydrocarbons. The tailoring of compression ratio, air/fuel ratio, spark timing, and intake manifold shielding is possible with a factory-produced vehicle. It is clear, however, that major problems could arise with many of the after-market conversions now in service if a MON grade of LPG were used. This is

particularly important as after-market conversions account for somewhat over 80% of the propane vehicles in service, the majority (90%) of which have a mono-fuel configuration. The majority of the vehicles converted under the Propane Vehicle Grant Program were more than one year old on conversion. Unless another solution is found to the octane degradation problems, the use of a reduced-octane LPG should therefore be confined to dual-fuel vehicles and to factory-converted vehicles, a relatively small proportion of the propane vehicle stock.

New chamber designs, electronic engine management, and systems for the injection of liquid propane may improve the performance of mono-fuel engines with respect to knock at high-compression ratios. These developments may provide a means to use a lower MON fuel as an alternative to improved power output and efficiency with the current HD-5 grade. Another possible approach in Canada could be to add MMT to the LPG to improve the octane number. No data are available on the effect of MMT in propane or LPG, but lead alkyls are very effective octane improvers, even at levels below that mandated for gasoline in 1987 (0.29 g/L) (Table 16). The addition of 0.5 g of tetramethyl lead (TML)/US gallon (0.132 g/L) to propane, an 80% propane/20% n-butane LPG, or to a mix close to the HD-5 specification (the blend was 90% propane, 5% n-butane, and 5% propylene) increased the MON by almost nine units. It appears that as little as 0.02 g of lead (as TML) would be required to upgrade the MON of an 80% propane/20% butane mix to the MON of HD-5 propane. While use of lead cannot be recommended, the scope for use of MMT, which is a permitted unleaded gasoline additive in Canada (at up to 0.018 g of Mn/L) should be measured not only for LPG enhancement but as a means to develop a high-MON propane for improved fuel economy.

9.5.5/ Fuel-Air Ratio

An increase in the butane content of automotive propane increases the density of the liquid fuel and, also, the vapour. The vapour density of an HD-5 grade would be increased by 15% by reformulation to a 50% n-butane LPG, and the energy content of the liquid would be increased by 5.5%. If the carburetor is adjusted to the optimum air/fuel ratio for the blend, a 5.5% increase in vehicle range and volumetric fuel consumption would be experienced, but if the air/fuel ratio were maintained at the optimum for the HD-5 blend, an over-rich fuel-air mix would be delivered to the carburetor. This would adversely affect fuel consumption and carbon monoxide, unburnt hydrocarbon, and NO_x emissions under cruise conditions and, at minimum, a power loss at wide-open-throttle operation.

New sensors that are under development for electronic engine management

in lean-burn gasoline engines may be applicable to the control of air/fuel ratios in LPG, but use of current oxygen sensors that control the air/fuel ratio to the stoichiometric level would not be effective with propane or propane-butane blends.

Dynamic systems capable of adjusting the air/fuel ratio with changes in the content of LPG are under development in Europe, where fuel variability is common.

9.5.6/ Conclusions on the Effect of Fuel Changes

The combination of the effects of butane addition on fuel efficiency, knock resistance, and cold start will lead to a serious degradation of vehicle driveability and availability when the fuel composition departs significantly from the norm of the HD-5 grade. The effect of fuel changes will be at the maximum with post-purchase conversions to mono-fuel systems, and it will not be possible to infiltrate any substantial quantity of n-butane into automotive LPG for use in these vehicles in the summer without either

- resetting the engine timing (and major changes with a degraded fuel quality) or
- creative formulation of the blends to avoid problems due to octane loss.

9.5.7/ Safety and Legislative Issues

The effect of butane addition on the safety of bulk storage, fuel transport tankers, and refuelling stations has already been discussed. The safety issues relevant at the vehicle user level include the following:

- All safety precautions applicable to propane must continue to be enforced.

- Further training and leak detection equipment recalibration may be required in view of the more stringent requirements and somewhat increased hazard that accompanies the use of butane-rich fuels. This hazard is due principally to the higher vapour density and lower volatility of butane compared to propane, the increased energy density of the liquid and vapour, and the reduced lower explosion limit of butane in air compared to propane in air.

The principal legislative issues that are involved with propane continue to apply to butane blends. Certain legislation concerning vehicle parking within garages and underground and the location and spacing of fuel storage tanks may need to be re-examined to ensure continuation of the excellent safety record of automotive propane.

10/ RESEARCH, DEVELOPMENT, AND ENGINEERING REQUIREMENTS

10.1/ A Perspective on Propane Fuel Quality

Canada is fortunate in having an established nationwide system for the production and delivery of high-quality (Grade 1, HD-5), high-propane-content automotive propane to over 4000 refuelling sites. Much consideration should be given to the merit of introducing another grade for summer season use. Although easy to achieve at the manufacturing level, a summer grade would complicate delivery and storage operations, with the potential for summer fuel carry-over into the winter season, thereby increasing cold-start problems.

Because of the wide availability of the high-quality HD-5 grade, the market for mono-fuel propane vehicles has grown much faster than that for the less efficient dual-fuel vehicles. This overwhelming choice of the higher efficiency mono-fuel systems should be encouraged and the less economic dual-fuel systems discouraged. Introduction of a lower octane automotive LPG would strengthen the argument for dual-fuel systems (which already have range and cold-start on gasoline advantages over the mono-fuel systems).

Since there is no impending shortage of automotive-quality propane, investigations with short-term objectives should aim to

1/ improve the performance of propane vehicles, with winter cold start being the first priority;
2/ improve the economics of propane use as a vehicle fuel;
3/ provide fuel quality to take advantage of the developments now under way in spark-ignition engines and control systems and in the expansion of propane use to large engines (trucks and buses).

The development of knowledge on the performance of vehicles using butane-containing automotive LPGs is a long-term strategy aimed at the situation beyond the year 2000 or so, a possibility that the demand for automotive propane may grow to such a level that augmentation of the supply may be necessary, or a possibility that butane is produced at rates greater than can be absorbed by gasoline and petrochemical markets. Long-term growth of the automotive propane market to require propane augmentation will be determined by the success of the shorter term objectives 1 to 3 just noted. Consistent with this, the principal objectives for work on a butane-propane mix should be to determine the fuel compositions and engine-vehicle configurations that will, at minimum, maintain the performance and economy of "propane" vehicles.

The long-term solutions include the following:

- must be compatible with both factory-produced and after-market conversion vehicles;
- cost-effective, since a competitive option already demonstrated at the pilot plant level is the surprisingly high (89 weight %) catalytic "hydroreforming" of butane to propane. If operated at large-scale the process could provide propane from butane at a conversion cost of 2 to 2.5¢/L.

10.2/ Research Projects

10.2.1/ Low-Temperature Fuel

1/ Objective

To define LPG formulations that can provide improved cold weather starting (start-and-run) under Canadian winter conditions.

The formulations will meet Canadian safety standards for vapour pressure (200 psig at 100°F) and octane value (95 MON).

2/ Procedure

Ethane addition to various blends of propane and butane will be examined to provide a range of fuels with a minimum vapour pressure of 200 kPa at -35°C, a maximum of 1435 kPa at 37.8°C.

The candidate fuels will be measured for octane number to select compositions with a MON of 95 or higher.

The best candidate fuels will be tested for cold start and cold running in a "conventional" propane engine with and without use of a block heater and in the optimum carburetion systems that are generated in the Chrysler tests (10.21 Low Temperature Operation -- Vaporizer Development and 10.22 Low Temperature Operation -- Cold Cranking and Starting Projects).

The fuel compositions will be consistent with segregation of gas-derived LPG streams (no propylene present) and will probably contain 7 to 10% ethane and up to 20% butane. Octane rating may require that the butane content be defined in terms of the maximum n-butane content, requiring the use of field butanes (with 30% isobutane content).

Cold room engine dynamometer testing and on-road testing at temperatures below -15°C will be needed to further evaluate the performance of the optimum blends.

10.2.2/ LPG Compositions with 95 MON and 95+ MON

1/ Objective
To define and evaluate commercially feasible fuel formulations containing less than 90% propane.

2/ Procedure
Calculations will be made of the vapour pressure, motor octane, and cost of a number of propane blends containing variable quantities of ethane, n-butane, isobutane, with and without small additions (up to 5% propylene). The calculations will provide a range of fuels with a MON close to 95 and another series of high-MON fuels (97+MON). It is anticipated that if propylene and pentanes plus components are eliminated, high butane content (15 to 20%) by volume can be tolerated at the MON 95 level and that high isobutane levels in the butane content will provide high-octane series. The exclusion of propylene and pentanes plus can be achieved by use of gas-derived LPG, which has no olefine components, and changes in the specification and method for processing refinery LPG.

Motor octane values will be generated for promising blends, which will then be tested for performance in engine dynamometer and road tests. The tests of high-MON fuels will include determination of the low-temperature performance (cold chamber engine dynamometer and cold-start tests) and the fuel(s) included in the compression ratio tests planned by Chrysler (Project 10.1 Compression Ratio Development).

10.2.3/ Antiknock Additive

1/ Objective
To provide formulations for high-octane automotive fuels.

2/ Procedure
Selected samples of low propylene, low pentanes plus LPG, and propane identified and characterized in Section 10.2.2 will be reformulated and tested using small quantities of MMT (up to 18 mg/L Mn). Tests of the octane enhancement will be made by the motor octane method and the highest level MMT fuels tested on an engine dynamometer using a carbureted and a throttle body injected fuel delivery system. Road tests and engine inspections similar to those proposed for Section 10.2.2 will be required to determine the driveability, fuel economy, and cold weather performance of the high-octane fuels.

The final outcome of the proposed tests will be to provide the equivalent of all-weather performance (including cold-start) data on new propane-containing fuel formulations, which could be produced in Canada to

- improve propane vehicle reliability and performance, including cost savings through improved fuel economy;
- meet a condition where the propane supply must be augmented by the addition of higher hydrocarbons.

11/ CONCLUSIONS

11.1/ Butane Augmentation of the Canadian Automotive Propane Supply

1/ Propane Supply/Demand Considerations

The combined supply of propane from natural gas and refinery production is expected to increase steadily at least until 1995. Canadian demand for propane in that period is expected to increase but at a slower rate than supplies, and the surplus available for export is likely to increase to 50% of supply.

While propane use as an automotive fuel in Canada is expected to increase beyond the current level of 20% of domestic propane demand, the surplus propane will be sufficient to power almost one million vehicles more than the estimated 1995 propane vehicle population of 235 000.

In view of this projected surplus, there appears to be little short-term rationale for the development of a new grade of LPG to stretch the supply of propane. The need may well lie beyond the year 2005.

2/ Butane Supply/Demand Considerations

Despite the large volume use of butane in the production of gasoline (to the extent that refiners are net consumers of butanes), supplies from gas separation plants and refineries are so large that 56% of Canada's net butane production was exported in 1985. The effect of the change in lead content in gasoline and eventual phaseout of lead use is uncertain, but it appears that it will involve an increase in the use of crude oil, with concurrent increase in propane and butane production. There will also be an increase in refinery use of butane in the form of butane combined in (refinery-produced) alkylate and MTBE (probably purchased from the chemical industry). This and the continued slow decrease in the gravity of crude oils processed will increase the production of refinery propane nationwide but is not expected to increase the availability of butane significantly. The availability of butane for exports may be reduced somewhat if plans to substitute butane for naphtha in the production of ethylene are followed.

In the period to 1995 it appears unlikely that there will be a need to develop a new market for surplus butane in a new grade of automotive LPG.

The US market for Canada's propane and butane may be affected by large surplus supplies available from North Sea and OPEC sources and aggressive marketing policies. However, this will affect both propane and butane

markets and does not provide a rationale for the displacement of propane in Canada's automotive fuel market by a propane-butane mix.

11.2/ Price Considerations

In Canada and the US, butane is sold at a substantial premium over propane (18 to 25% premium on a volumetric basis) and, as concluded, there are no supply/demand reasons to cause a significant change in this relationship in the future. The production of a mixed LPG will not result in any significant savings in production costs: the facilities for fractionation of LPG to specification-grade propane and butane and their storage already exist and only modest savings in energy costs in fractionation would be achieved. Substantial expense would be incurred in the distribution and marketing of a summer grade and a winter grade of automotive propane. In fact, propane for heating purposes is not now segregated from the automotive grade for this reason.

If propane engine control systems are developed to take advantage of the increased energy content of a butane-propane blend, then some operating cost savings (up to 2.5% for a 50:50 blend of propane and butane) could be achieved. In the present engines a modest loss or no effect on fuel economy is anticipated.

Butane could be converted into propane in high yield in a new plant or modified butane isomerization plant. A premium estimated at 2 to 2.5¢/L for propane over butane would be required to justify the conversion. Such a premium is unlikely to develop in the period 1995 to 2005. Such a low realization for butane would encourage its retention in gasoline as a blending component, as a component of alkylate or MTBE, and would find expanded use in the production of ethylene and other petrochemicals (acetic acid and maleic anhydride).

11.3/ Performance Considerations

The nationwide availability of a consistent quality high-octane fuel across Canada has permitted the development of an efficient fleet dominated by mono-fuel conversions rather than widespread use of less efficient dual-fuel vehicles, which is required in Europe in view of the inconsistent composition and low-octane rating of the automotive LPG sold there.

Cold-start problems are severe in Canada and would be increased if a butane-containing LPG grade were introduced, since a summer grade of fuel is certain to find its way from time to time into the low-butane HD-5 specification winter grade.

It is also concluded that, since a number of after-market conversions have been reported to give marginal performance even with HD-5, introduction of a lower octane grade would court more problems and have a negative impact on future conversions.

11.4/ Key Issues

- The position of propane vehicles in the automotive market is too precarious at this time to justify early introduction of any measure which will complicate or increase the cost of owning and operating a propane vehicle.

- The effect of a change in the LPG composition must be transparent to the consumer, except in terms of improved fuel economy or cost.

- There are serious safety implications involved in the introduction of high levels of butane into an automotive fuel, which must be resolved before the fuel can be considered for widespread distribution.

- A new grade of propane, if introduced, should be formulated to provide improved performance or fuel economy. New formulations would be effective in mono-fuel vehicles and useful at the earliest date in factory-produced vehicles or where, as in buses and trucks, vehicles are re-engined to accommodate the fuel change.

11.5/ Research and Development on Fuels

There is an opportunity to improve the cold weather, fuel economy, and year-round driveability of propane vehicles by the use of specially formulated propane-based fuels used in modern technology engines. It appears that more rigorous selection of the source of the propane used in automotive applications and the use of additives, such as ethane and MMT, should be investigated as means to improve fuel performance and to permit the future use of butane in the fuel as and when the addition becomes economic.

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R.F. Webb Corporation Ltd., et al., "An Evaluation Study of the Propane Vehicle Grant Program"(Draft Final), Energy, Mines and Resources Canada, Program Evaluation Branch and Transportation Energy Division, Ottawa, August 1986.

Williamson, E.I., "Gases as Alternative Motor Fuels - Where Do We Go from Here?" Institute of Petroleum, London, England, IP85-004, 1985.

Table 1/ Production of Propane and Butanes in Canada (excludes producers'own use)

Thousands of m^3/day

	PROPANE PRODUCTION			BUTANES PRODUCTION			TOTAL LPG PRODUCTION		
	Gas Plants	Refineries	Total	Gas Plants	Refineries	Total	Gas Plants	Refineries	Total
1974	14.5	2.8	17.3	9.7	1.0	10.7	28.0	3.8	31.8
1979	15.6	4.2	19.8	9.9	2.5	12.4	25.5	6.7	32.2
1980	14.8	3.9	18.7	9.3	3.3	12.6	24.1	7.2	31.3
1981	14.5	3.7	18.2	9.2	3.9	13.1	23.7	7.6	31.3
1982	14.8	3.6	18.4	8.5	3.9	12.4	23.3	7.5	30.8
1983	13.4	4.0	17.4	8.6	4.9	13.5	22.0	8.9	30.9
1984	14.2	4.2	18.4	8.8	4.9	13.7	23.0	9.1	32.1
1985	14.9	4.0	18.9	9.0	5.0	14.0	23.9	9.0	32.9

Millions tonnes/year
1985[1] Propane 3.64 Butanes 2.95 LPG 6.6

Note: [1]propane sp.gr. 0.508; mixed 70%-30% isobutanes sp.gr. 0.572

Source: R.F. Webb Corp. Ltd. summary of EMR data (Energy Statistics Handbook)

Table 2/ Canada's LPG Supply and Demand, 1975-1985 (m^3/day)

		Propane	Butanes	LPG Total
1975	Supply	18.1	10.9	29.0
	Canadian demand	8.2	5.2	13.4
1980	Supply	18.7	12.6	31.3
	Canadian demand	7.9	5.5	13.4
1985	Supply	20.0	12.4	32.6 (112% of 1975)
	Canadian demand	12.0	5.5	17.5 (131% of 1975)

Note: Supply is marketable product after the internal requirements of gas plants and refineries are met.

Source: R.F. Webb Corp., with data from EMR (Energy Statistics Handbook) and National Energy Board 1985 Annual Report.

Table 3/ Gas-Based LPG Production in Canada Forecasts for 1984-1995 and 2005 (m^3/day)

	1984	1990	1995	2005?
Propane				
Gas plant production	15 870	21 000	19 000-21 000	14 000
Frontier supply	0	0-400[1]	400-1650[2]	1500[2]
Butanes				
Gas plant production	8740	11 500	10 400-11 500	8000
Frontier supply	0	0-250[1]	250-1000[2]	1000[2]
Total gas-sourced LPG	24 610	32 500-33 150	30 050-35 150	24 500

Notes: [1]minimum Venture Field extraction or start-up of Hibernia
[2]Hibernia and/or Venture operating

Source: NEB estimates of 1984 reworked for frontier supply

Table 4/ Simple Fuels Refinery: LPG Balance (80 000 barrels/stream day)

	ORIGIN						DESTINATION								
							Gasolines					Other			
Component	LPG Import	Crude Import	FCC Prod	Rfmr Prod	Hycr Prod	TOTAL PROD	C4 Alkyl	LR Sales	UR Sales	UP Sales	Olefin Sales	LPG Sales	C3 Mix Sales	Ref Fuel	TOTAL CONSUM
Propane		599	659	656		1914						1628	57	229	1914
Propylene			1112			1112					793		119	200	1112
Butylene			1472			1472	1004	244	197	27					1472
Isobutylene			519			519	358	77	75	9					519
Isobutane	170	370	1725	170		2435	1597		247	591					2435
N-Butane	1404	805	471	209		2889		799	1982	107					2888
	1574					10341									10340
NET					8767										8767

Key: LR = leaded regular
UR = unleaded regular
UP = unleaded premium
C3 Polym (propylene) = polymer gasoline
C4 Alkyl = butane-butylene alkylates

Table 5/ Petrochemicals Refinery: LPG Balance (80 000 barrels/stream day)

	ORIGIN								DESTINATION						
									Gasolines				Other		
Component	LPG Import	Crude Import	FCC Prod	Rfmr Prod	Hycr Prod	TOTAL PROD	C3 Polym	C4 Alkyl	LR Sales	UR Sales	UP Sales	LPG Sales	C3 Mix Sales	Ref Fuel	TOTAL CONSUM
Propane		216	425	1238	658	2537						2043		494	2537
Propylene			1042			1042	1042								1042
Butylene			883			883		883							883
Isobutylene			311			311		311							311
Isobutane		535	723	486	801	2545		1430	311	212	592				2545
N-Butane		719	233	605	801	2358			503	674	163	1018			2358
						9676									9676

Key: LR = leaded regular
UR = unleaded regular
UP = unleaded premium
C3 Polym (propylene) = polymer gasoline
C4 Alkyl = butane-butylene alkylates

Table 6/ The Effect of Season on N-Butane Blending in Gasoline/Ontario Refinery Producing Leaded and Unleaded Grades[1]

SUMMER GASOLINES COMPOSITION

Gasoline Source in Refinery	Component RVP[2]	Volume % in Regular Gasoline Unleaded	Leaded
N-butane	52	9.3	6.3
Light straight-run gasoline	10.4	1.3	38.8
Fluid cat crackate	4.5	35.0	48.2
Reformate	5.0	24.7	6.7
Polymer gasoline	4.5	-	-
Alkylate	5.6	29.7	-
Gasoline property			
RON		92.5	93.6 87.2 clear[3]
MON		85.7	84.6 78.9 clear
R+M/2		89.1	89.1 83.0 clear
RVP (psia)	11.0	10.9	

SEASONAL VARIATION IN MAXIMUM BUTANE VOLUME %

	Max. RVP Regulation	Volume % N-Butane Unleaded	Leaded
November to February	14.9	15.7	13.2
March and October	13.9	14.0	11.4
April	13.0	12.5	9.9
May to September	11.0	9.2	6.5

Notes: [1]14 181 BPD unleaded, 16 709 leaded per day
[2]RVP = Reid vapour pressure (psia)
[3]Clear values refer to blended gasoline octane value before tetraethyl lead addition.

Source: R.F. Webb Corporation Ltd.

Table 7/ Forecasts of Refinery LPG Net Production

Net Supply	Net Refinery Propane and Butane Production (m^3/day)			
	1984	1990	1995	2005?
Propane, NEB forecast	3600	3100	3200	3400
Propane, producer group forecast	3400	4050	4080	-
Butane supply, NEB	2670	2200	2270	2400
Butane calculated[1]	2520	2870	2890	-

Note: [1]calculated from producers' propane forecasts

Table 8/ Butane and Crude Back-Out Summary

		Refinery Import BPD					Export	Back-Out Ratios as % Base Vol.				
Case Name	Pb Level (g Pb/L)	Vol. % Oxyg in gasoline	Oxyg	Crude	nC4	iC4	C3	nC4	Crude	C3	nC4	iC4
Base case												
	0.29	0	0	58709	521	1596	1150	0				
	0	0	0	59323	35	1575	1273	0				
Oxinol												
	0.29	9.5	2935	56348	0	1448	934	315	4.02	0.36	1.42	0.25
	0	9.5	2935	57827	0	1454	1274	1018	2.52	0.6*	1.78	0.20
V-Plus												
	0.29	9.5	2935	56345	0	1441	939	276	4.03	0.36	1.36	0.26
	0	9.5	2935	57787	0	1444	1288	921	2.59	0.6*	1.61	0.22
MTBE												
	0.29	10	3089	54838	757	1303	840	0	6.59	0.5	0.4*	0.5*
	0	10	3089	56542	0	1370	1126	126	4.69	0	0.27	0.35*

Note: *represents an increase in propane-butane supply requirement

Table 9/ Example: Butane Use in Oxygenated Gasoline Production[1]

		Import for Blending and Alkylate		Imported as Oxygenate (Butane Equivalent)	Export	Net Volume of "Butane" Used	Butanes as % Crude Run[2]
		nC4	iC4		nC4		
Base case	(0.29 Pb/L)	521	1596	0	0	2117	3.6
	no lead	35	1576	0	0	1610	2.7
MTBE	0.29 g Pb	757	1303	2780	0	6324	11.5
	0	0	1370	2780	126	4024	7.1
Oxinol	0.29 g Pb	0	1448	1525	315	2658	4.7
	0	0	1454	1525	1018	1961	3.4

Notes: [1]case as for Table 8
[2]butanes as volume % of crude run in each case

Table 10/ LPG Balance in a Syncrude Refinery

LPG Volume % of Crude Oil Used	Syncrude Refinery[1]	Conventional Refinery
Butanes purchased (iso)	0	(2.08)
Butanes exported (normal)	10.2	0.72
Propane exported	2.3	2.3
Total net LPG export	12.5	0.94

Note: [1]Exports also include benzene at 10.9 volume % of syncrude run.

Source: Padgett Process Services Ltd., private correspondence

Table 11/ Summary of Factors Affecting Propane and Butane Balance in Refinery

Factor	Propane	N-Butane	I-Butane
Increase crude throughput	E+	E+ (summer)	I+
Increased syncrude	E+	E++	I- (to zero)
Extract petrochemical (BTX)	E+	E++	I-
Lead reduction			
(a) no oxygenates	E+	I-	N/C
(b) MTBE	N/C	I- (I+ with lead)*	I- (I++)*
(c) Oxinol	N/C	E+	I- (I++)*
Summer vs winter	N/C	E+ (summer) I+ (winter)	N/C

Key: E = net export
I = net import
N/C = no significant change from base case (leaded, no oxygenate)
*(I+) = increase in imports when i-butane content of MTBE and t-butanol are included

Table 12/ Butane, Propane and Crude Oil Price Relationships (Average 1976-1984)

	SARNIA As % of Cost of Crude Oil in Toronto	
Propane	Wholesale Canada	70.5(1)
	Export	62(2)
Butanes	Wholesale Canada	88(1)
	Export	78(2)
	EDMONTON As % of Cost of Crude Oil in Edmonton	
Propane	Wholesale Canada	56.5(3)
	Export	46(4)
Butanes	Wholesale Canada	79(3)
	Export	67(4)

Notes: (1)Crude cost in Toronto is former "blended" domestic price.
(2)Crude cost in Toronto is "landed import cost."
(3)Crude cost in Edmonton is blended price Montreal less transport cost Edmonton to Montreal.
(4)Crude cost in Edmonton is "landed import cost."

Source: R.F. Webb Corp. using fuel cost data supplied by EMR Canada

Table 13/ Automotive LPG Blend Standards or Practice for Selected Countries

(Propane volume percentage/butane and higher percentage)

	Year Round	Summer	Winter	Note
Canada, USA	90/2.5			5% propylene max.
United Kingdom	89/11			
Sweden	95/5			
Netherlands	50/50	40/60	60/40	60 kPa min. vapour pressure at -15°C in winter
Belgium	40/60	20/80	50/50	
Italy	25/75			
Spain	30/70			
France	35/65			
W. Germany	90/10			

Source: Institute of Petroleum, London, England, IP85-004, 1985

Table 14/ Properties of Propane and Butane Related to Garage and Refuelling Facility Safety

	Propane	Butane
Vapour density relative to air	1.52	2.0
Lower explosion limit in air, %	2.4	1.9
Ignition temperature, °C	493-549	482-538
Flame temperature (maximum), °C	1982	1996

Source: "Ontario Propane Storage, Handling and Utilization Code," Canadian Gas Association, CAN1-B149.2-M80, 1983.

Table 15/ Specific Operational Problems Cited by Propane Vehicle Grant Program (PVGP) Grantees

Priority		Number
1	Cold start	22
2	Too frequent tune-up, too much downtime	10
3	Too few fuelling stations	8
4	Improper/poor quality conversions	7
5	Power loss	5
6	Valves -- burn out	4
7	Low quality of conversion kits	3
7	Conversion cost too high	3
7	Promoters do not stand by product	3
7	Interior heating poor in winter	3
7	Drivers do not like, or are afraid of, fuel	3
7	Fuel cost too high	3
7	Lack of technical information	3
13	Not enough maintenance shops	2
13	Cold weather fuelling problems	2
13	Safety concerns	2
13	Added cost of propane trained staff	2
13	Engine runs hotter than gasoline	2
13	Inadequate warranty support	2
13	Filter plugs	2

Others: lack of promotion; grant not indexed to cost; cannot fix vehicles on spot; investment in fuel deport required; fuel gauge problem; new vehicles not suited to carburetion of propane; poor parts availability and cost; dealer "monopoly" of parts supplies (too few sources)

Number of comments: 107
Number of respondents with comments: 40

Source: Webb et al, "An Evaluation Study of the Propane Vehicle Grant Program," EMR, 1986.

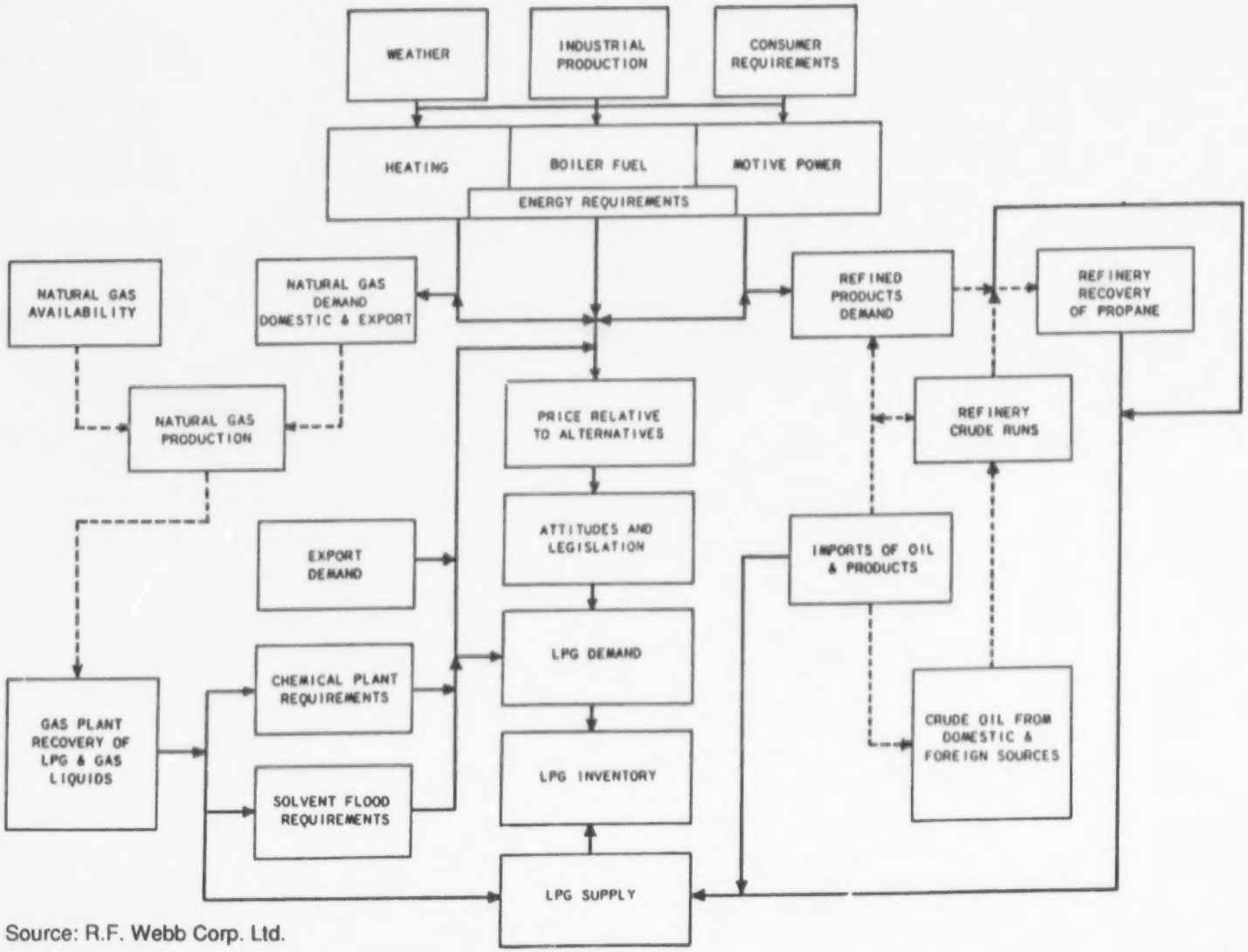
Table 16/ Effect of Tetramethyl Lead on Octane Numbers of LPG

	TML g/Pb per US gal	Gain in RON	Gain in MON
Propane	0.5	9.6	8.7
Propane 90% + 5% n-butane	0.5	8.7	8.4
+ 5% propylene	1.0	-	12.2
Propane 80%, n-butane 20%	0.5	8.4	8.9
	1.0	-	13.4
	3.0	-	20.0

Source: Adams and Boldt, "What Engines Say About Propane Fuel Mixtures," SAE Paper 938C, 1964.

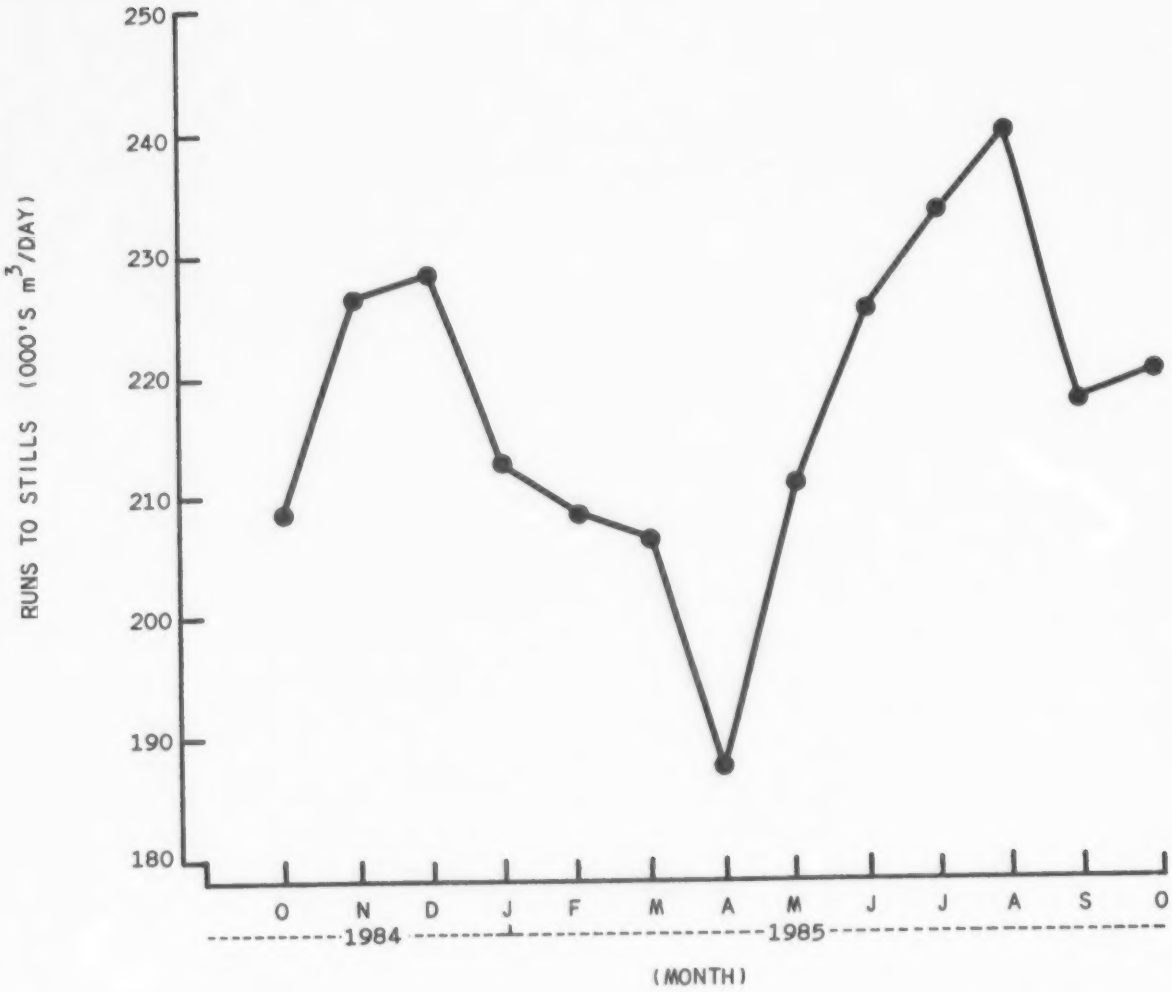
SUPPLY	DEMAND	MARKET SHARE
- Resource Availability	- Supply Constraints on Competitive Fuels in Transport Market	- Relative Supply Price
- Gas Plant Production	- Heating Fuel Market	- Equipment Conversion/Premium
- Refinery Production	- Petrochemicals	- Local Availability
- Imports	- Solvent Flood	- Performance
- Crude Oil Refining	- Exports	- Efficiency
		- Tax and Subsidy
		- User Perceptions
		- Legislative Barriers/Aids

Figure 1/ Factors Affecting Market Penetration of Automotive LPG



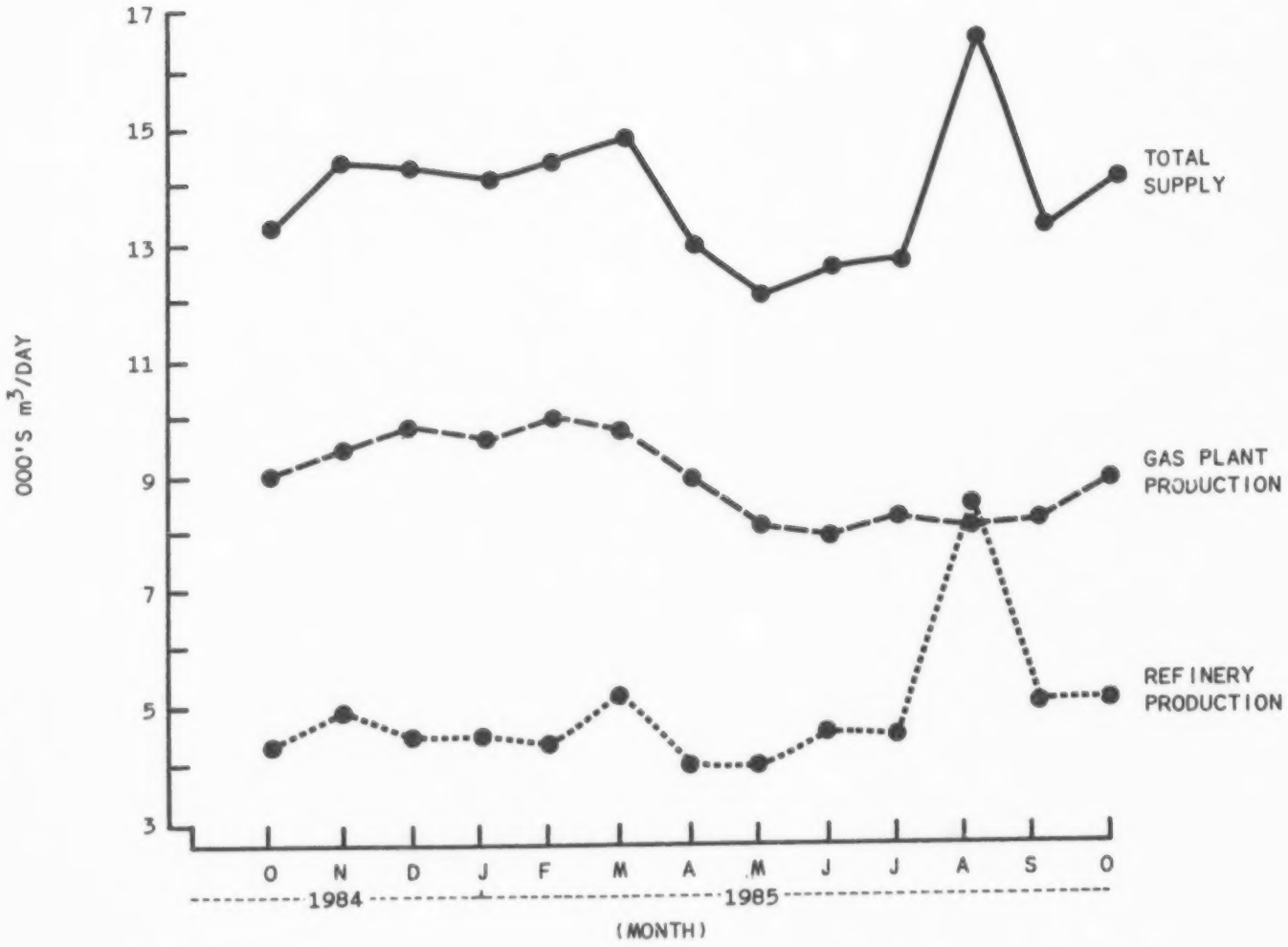
Source: R.F. Webb Corp. Ltd.

Figure 2/ A Model of the Canadian LPG Industry



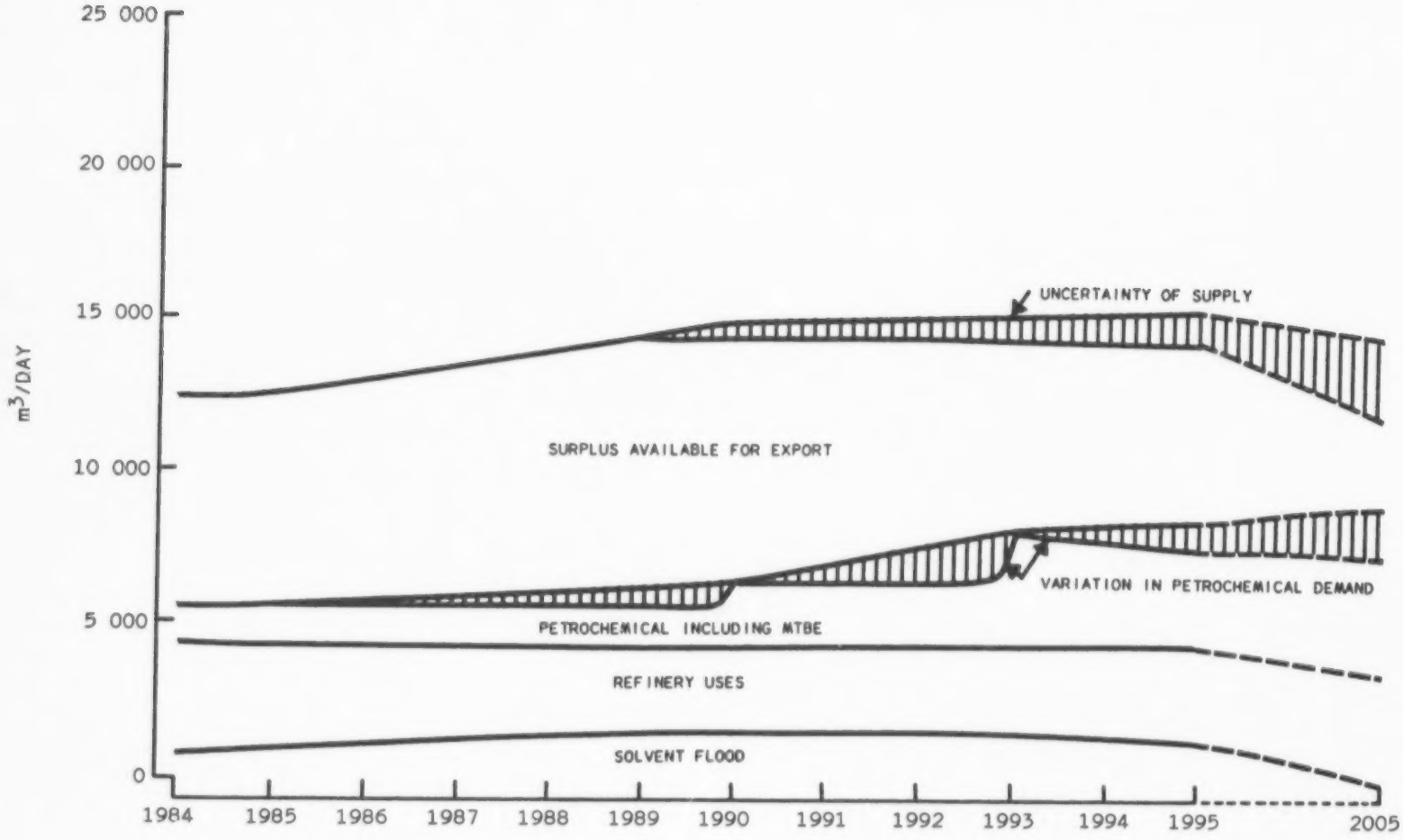
Source: R.F. Webb Corp. and data from Energy, Mines and Resources Canada, *Energy Statistics Handbook*, Table 3.14

Figure 3/ Crude Runs to Stills in Canada, 1984-1985 (Crude Oil and Equivalent 000's m^3/day)



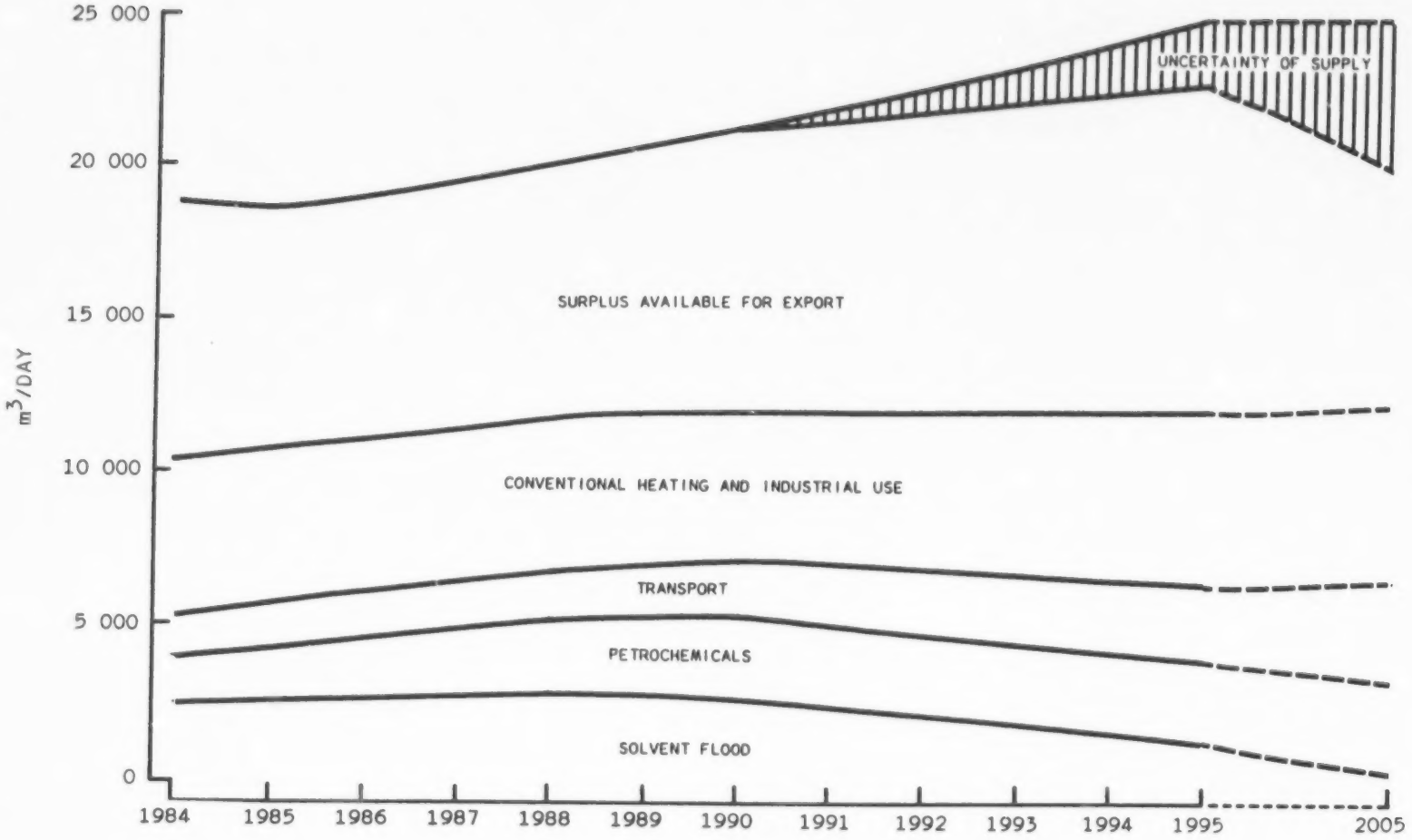
Source: R.F. Webb Corp. and data from Energy, Mines and Resources Canada, *Energy Statistics Handbook*, Table 3.14

Figure 4/ Monthly Butanes Supply in Canada



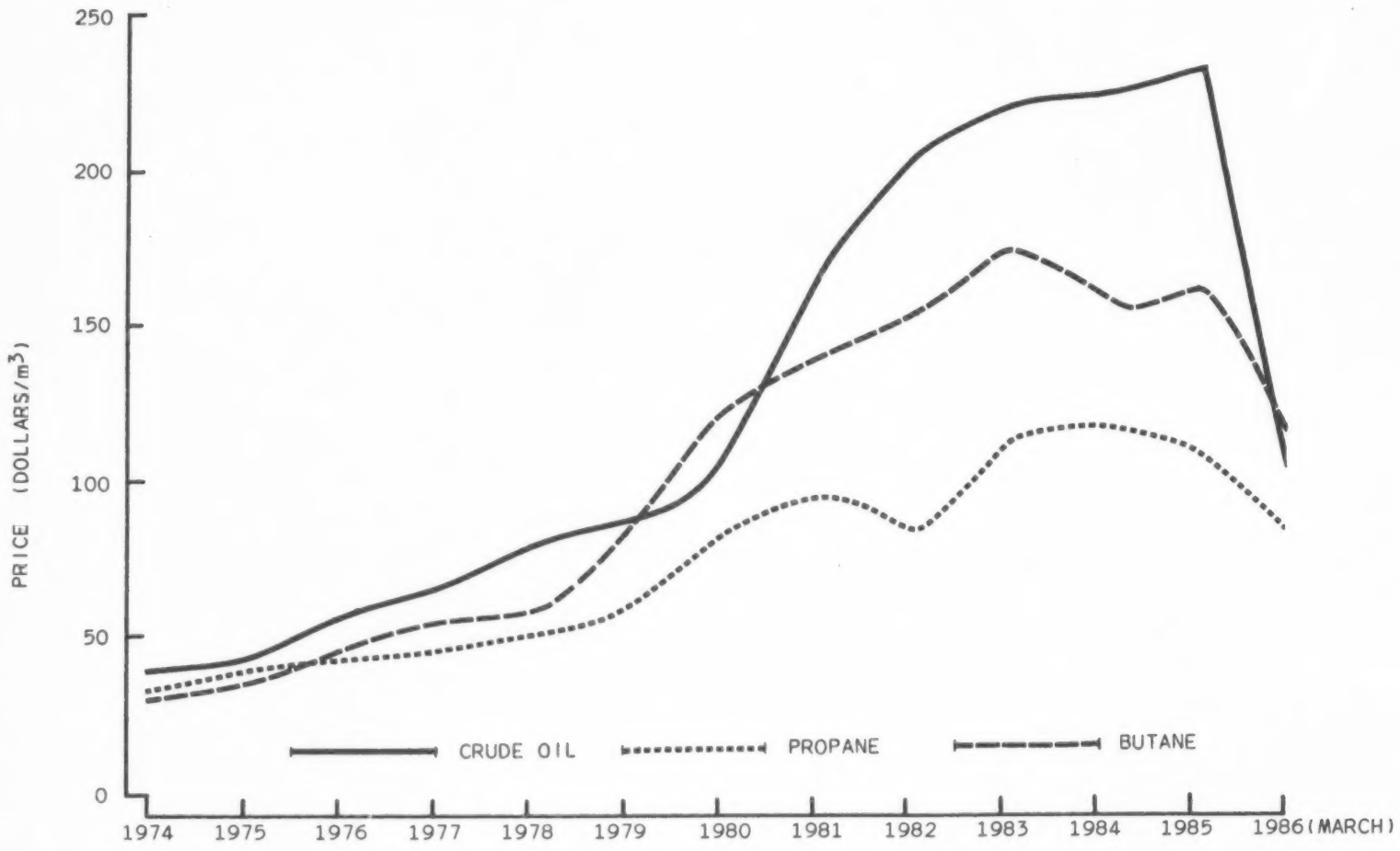
Source: R.F. Webb Corp. (revision of NEB and industry forecasts)

Figure 5/ A Forecast of Canada's Butane Supply and Demand



Source: R.F. Webb Corp. (revision of NEB and industry forecasts)

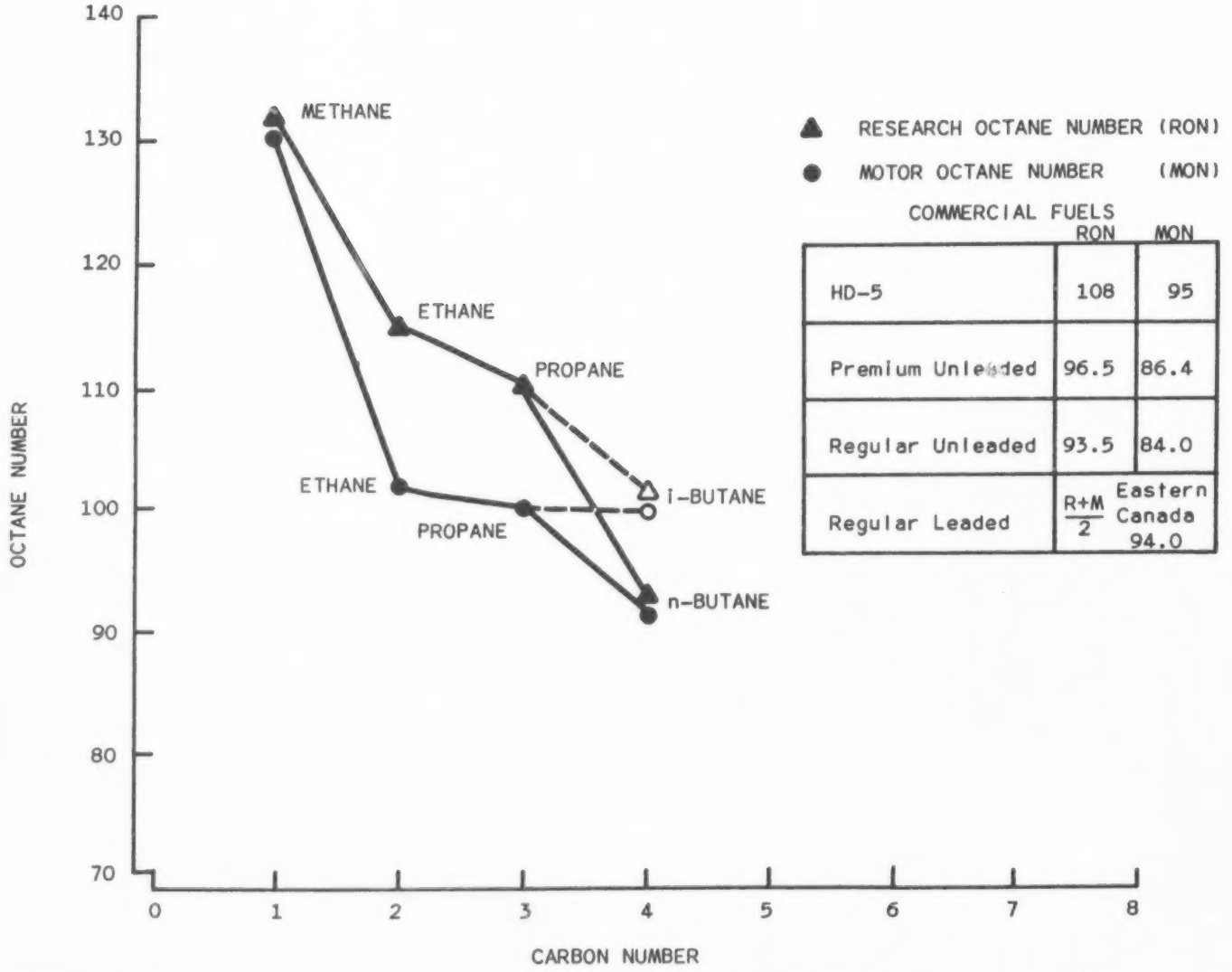
Figure 6/ A Forecast of Canada's Propane Supply and Demand



(1) Crude oil average wellhead cost plus gathering fees, pipeline tariffs, and petroleum corporation charge. Butane and propane are average wholesale price ex gas plants in Alberta.

Source: R.F. Webb Corp. from EMR data *(Energy Statistics Handbook)*

Figure 7/ Butane, Propane, and Crude Oil Wholesale Price in Alberta (1)

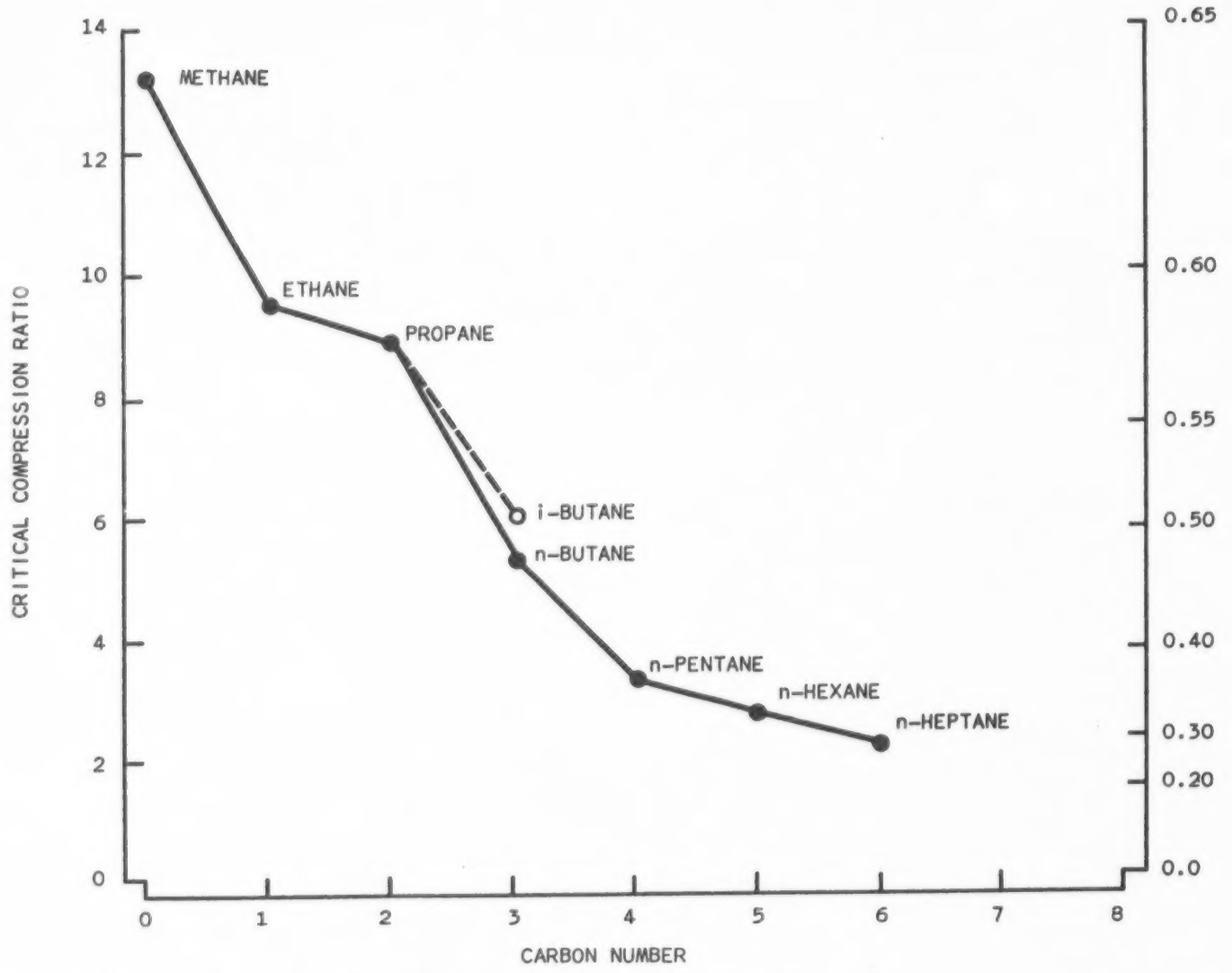


COMMERCIAL FUELS

	RON	MON
HD-5	108	95
Premium Unleaded	96.5	86.4
Regular Unleaded	93.5	84.0
Regular Leaded	$\frac{R+M}{2}$ Eastern Canada	94.0

Source: Data from Kirk-Othmer, *Encyclopedia of Chemical Technology*, 2nd ed., 1966, Vol. 10, p. 496

Figure 8/ Octane Values for Hydrocarbons



Source: Goodger, E.M., *Hydrocarbon Fuels*, MacMillan Press Ltd., London, 1975, p. 172

Figure 9/ Critical Compression Ratios for Hydrocarbons